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New Developments of Limit States Design for the New GDR Timber Design Code

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New Developments of Limit State Design for the New GDR Timber Design Code

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1. Introduction

An improved exploitation of the mechanical properties of timber and timber material requires the continuous improvement of the calculation and design methods or the introduction of new methods, respectively.
The change from design methods adopting admissible stresses to methods adopting limit states in timber construction is an initial step towards a probabilistic safety concept. As compared with the method by admissible stresses, the method by limit states renders it possible to cover and record more exactly by calculation the degree of loading of the built-in material subject to the actual state of utilization. Thus, the exploitation of the available materials can be improved.

Reference /1/ reports the beginning of the research work in this field.
Other papers (see references /2/ to /5/) have been published recently.

The present state of preparation of the future Timber Design Code is being described hereinafter. The results and findings were provided by implementing a close co-operation and teamwork between the GDR research institutions and establishments concerned.
The work and activities performed hitherto resulted in defining initial regulations for the future design code, such as - inter alia - for the symbols and definitions, standard and basic values of the design strengths as well as the adaptation factors. The structural arrangement of the design code is being specified on the model of the ISO and CIB Codes (see references /6/ and /7/) and according to the GDR Codes and Standards being applicable at present /8/. The designations comply in the main with those of the ISO Code /6/ (see Table 1).

2. Limit States

The limit states are distinguishable into the following two types :-

(A) limit states of the load-carrying capacity (GZT)
(B) limit states of the usability (GZN)

2.1. Limit States of the Load-Carrying Capacity (GZT)

During the whole service life of a building or structure, the maximum possible stress and loading must be smaller than or equal to the minimum possible loadability of the material concerned.
An exceeding of this limit state results in a complete unserviceability or failure of the timber structure.
The checks of the GZT limit states include the following :-
- strength of the loadbearing members
- strength of the connections
- stability of the loadbearing members
- overturning, lifting of the building/structure, and the like.

The checks of the GZT limit states can be established by means of equation (1) for the design values, by means of equation (2) for the internal forces, or by means of equation (3) for the stresses.

$$S \leq R_F \qquad (1)$$

or $$M;\ N;\ V \leq R_M;\ R_N;\ R_V \qquad (2)$$

or $$\sigma \leq R \qquad (3)$$

S = design value of the load
R_F = design value of the acceptable load
M, N, V = design values of the internal forces
R_M, R_N, R_V = design values of the acceptable internal forces
σ = design value of the stresses
R = design value of the strength

The design values of the loads are calculated by means of equation (4).

$$S = \gamma_n \left(\sum_{i=1}^{n} F_i^n \cdot \gamma_{f,i} + \psi \sum_{j=1}^{m} F_j^n \cdot \gamma_{f,j} \right) \qquad (4)$$

with $i = 1...n$ being the index for continuous and long-term actions/influences
$j = 1...m$ being the index for short-term and sudden actions/influences
γ_n according to Table 2 from /14/
ψ according to Table 3 from /15/
γ_f according to Table 4 from /15/

The design values of the internal forces and stresses are provided by analogy with this.

The design value of the strength is provided by means of equation (5).

$$R = R^{o} \cdot \Pi \cdot \gamma_{m,i} \qquad (5)$$

R^{o} = basic value of the design strength

$\gamma_{m,i}$ = adaptation factors

2.2. Limit States of the Usability (GZN)

During the whole service life of a building or structure, the deformation of the construction due to the standard loads must be smaller than or equal to its limit value according to the design/project. An exceeding of this limit state restricts the utilization of the construction as specified by the design/project.

$$u \leqq u \qquad (6)$$

$$\text{with } u = \sum_{i=1}^{n} u_i^n + \Upsilon \sum_{f=1}^{m} u_j^n$$

With u_i^n being the deformation due to the standard value of a continuous or long-term action/influence

u_j^n being the deformation due to the standard value of a short-term action/influence

The checks of the GZN limit states include the following :-

- deformation of the loadbearing members
- vibrations/oscillations of the loadbearing members
- positional changes of the building/structure

3. Sorting by Strength Grades

The reliability and efficiency of the design methods in timber construction can be increased considerably by adding in future the sorting parameters of mechanical sorting such as volume weight (bulk specific gravity) and modulus of bending elasticity to the sorting parameters of the hitherto prevailing visual sorting such as knots, splits, grain deviations, wingginess and the like. Looking at the coefficients of correlation

between sorting parameters and strength properties as shown in Table 5, one will see that the modulus of bending elasticity on the one hand and the knottiness and volume weight on the other hand have the same correlation with the strength properties.
The highest correlation with the strength properties is being provided by the modulus of bending elasticity in connection with the knottiness. A comparison with line 1 of Table 5 shows that the mechanical sorting is superior to the visual sorting.

Internationally, a classification/grading of the timber is being effected according to the characteristic strength which nowadays is consistently defined as 5 % quantile of a three-parametric Weibull distribution if the characteristic values were determined by tests in structural timber dimensions. The characteristic strength corresponds to the standard value of the design strength.

In general, the characteristic strength of faultless specimens is being determined by means of the normal distribution.

4. Basic Values of the Design Strengths

The basic values of the design strength are being derived from the standard values of the design strengths (5 % quantiles).

$$R^o = \frac{R^n(0.05)}{\gamma_{m,o}} \cdot K_{mod}$$

with $K_{mod} = k_e \cdot k_t$

K_{mod} = modification factor for transforming the design strength to normalized grades of moisture and load duration

k_e = modification factor as to climatic grade

k_t = modification factor as to load-duration grade

$\gamma_{m,o}$ = material factor

The material factor $\gamma_{m,o}$ is a partial safety factor consisting of several single factors (see Table 6) by means of which the possible uncertainties in the actual behaviour of the construction or structural unit, respectively, and the calculation/design results shall be covered.

In the GDR, material factors were not yet defined since further basic and fundamental studies and investigations are still required. This is the reason why initially only the standard values of the strengths are being indicated. Table 7 includes the standard values for individual types of stress and strain checked and tested by means of experiments.
The standard values are indicated for structural timber being sorted visually according to the quality grade of same, for structural timber being sorted mechanically according to the specific strength grade (see Figure 1).
Concerning glued laminated timber, in future 6 grades will be included in the Code. The structure/design and arrangement of same is shown in Figure 2. The individual grade 1 to 3 layers of the boards are being sorted visually whereas those of grade 4 to 6 are being sorted mechanically (see Table 8).

Tests and experiments to determine the basic values of the grades 4 to 6 of glued laminated timber are being prepared at present.

5. Adaptation Factors

The adaptation factors $\gamma_{m,i}$ cover the systematic deviations or variations in the strength and deformation behaviour of the structural timber and glued laminated timber, of the timber fasteners and of the constructions occurring under real conditions of stress and strain.
The following 4 adaptation factors will be taken into consideration in the future Timber Design Code :-

$\gamma_{m,1}$ = adaptation factor as to long-term behaviour
$\gamma_{m,2}$ = adaptation factor as to cross-sectional height
$\gamma_{m,3}$ = adaptation factor as to curvature of timber
$\gamma_{m,4}$ = adaptation factor as to aggressive media

5.1. "Long-Term Behaviour" Adaptation Factor $\gamma_{m,1}$

It covers the complex influence exercised by magnitude of loading, duration of loading, moisture of timber, and temperature.

Based upon the references /2/ and /9/, 3 moisture grades, 3 time grades and 2 temperature grades will be included in the future Code (see Tables 9a to 9d) in order to determine the adaptation factor $\gamma_{m,1}$. The adaptation factor decreases with an increasing duration of loading and temperature (see Table 10).

5.2. "Cross-Sectional Height" Adaptation Factor $\gamma_{m,2}$

Table 11 indicates the adaptation factor $\gamma_{m,2}$ for structural timber and glued laminated timber subjected to flexural load. The reduction of strength begins above h = 200 mm for structural timber and above h > 300 mm for glued laminated timber. According to reference /9/, the adaptation factor $\gamma_{m,2}$ for glued laminated timber is also in line with the actual Code which is still based upon the method of the admissible stresses (see Table 11).

5.3. "Curvature of Timber" Adaptation Factor $\gamma_{m,3}$

Due to curvature, a reduction of the flexural strength of the structural timber or glued laminated timber takes place (see Table 12). The reduction occurs in accordance with the Swiss Code /12/.

5.4. "Aggressive Media" Adaptation Factor $\gamma_{m,4}$

The adaptation factor is being indicated in Tables 13a and 13b for structural timber and glued laminated timber subject to the degree of load, stress and strain imposed by the aggressive media (such as - e.g. - salts, acids, bases, vapours, gases).

Timber is resistant to weak acids with normal room temperature and to alkaline solutions of a low concentration. A corrosive action will occur only due to strongly acid and strongly alkaline solutions. In general, no timber corrosion is to be expected within the pH-value range of $2 < pH > 11$ /10/. With the majority of chemicals in a solid, liquid and gaseous state, the corrosive action decreases in the course of time and a destruction occurs only within the zone near the surface.

Investigations of timber beams installed in old structures of the potash industry resulted in observing a strength reduction caused by K 40 type potash salt only in the boundary/end zone of 10...20 mm (with an age of the structure concerned amounting to 54 years).
Separate investigations of pine-wood test specimens taken from a conveyor bridge being 54 years old showed that there were considerable differences in strength between the boundary and inner zones which were caused by the action/influence of nitro-chalk (see Figure 3).

The cross-sectional dimensions influence the corrosive action of the aggressive media. This is the reason why the adaptation factors were defined subject to the cross section of the timber However, the corrosive action is also influenced by protective/preservative systems being applied additionally (see the Tables 13a and 13b).

6. Further Research

In order to prepare the future GDR Timber Design Code by adopting the method of limit states, comprehensive studies and investigations are still required with structural timber and glued laminated timber as well as with timber connections/ fasteners.

The tests planned until 1988 will serve to determine standard and basic values of the design strength, standard and basic values of the modulus of elasticity and shear modulus, and to determine adaptation factors (see Table 14).
The investigations to determine standard and basic values of the design strength are concentrated on research activities and papers concerning the strength of structural timber and glued laminated timber subjected to flexural load and compressive stress as well as of nailed and dowelled connections.

The research activities and papers to determine adaptation factors are concentrated on the long-term behaviour adaptation factor, including the influence of the moisture of timber, the cross-sectional height in case of glued laminated timber, and aggressive media.

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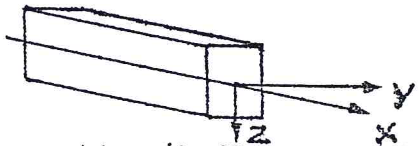
Table 1: Designations

symbol	dimension	designation
l	(m, mm)	length, effective span
b	(mm)	width
h	(mm)	height
t	(mm)	thickness
r	(mm)	radius
d	(mm)	diameter
a	(m, mm)	spacing/distance
e	(mm)	eccentricity
α	( )	angle
ϱ	($\frac{1}{mm}$)	curvature
A	(mm^2)	area
V	(mm^3)	volume
J	(mm^4)	moment of inertia
W	(mm^3)	moment of resistance
S	(mm^3)	static moment
i	(mm)	radius of inertia
λ	(-)	slenderness coefficient
φ	(-)	buckling coefficient
u	(mm)	displacement
ϑ	(^{o})	torsion
x,y,z		coordinates



symbol	dimension	designation
F	(kN,N)	action/influence, force, load
F^n	(kN,N)	standard value of the action/influence
W	(kNm, Nm)	work
m	(kg)	mass/weight
	($\frac{kg}{m^3}$)	density/specific gravity
t	(h,s)	time
T	(^{o}C)	temperature
u	(%)	moisture of timber
	(%)	relative air humidity
M	(kNm,Nmm)	moment, flexural moment
N	(kN,N)	longitudinal force
V	(kN,N)	shear force, lateral force
p	($\frac{N}{mm^2}$)	pressure/compression
σ	($\frac{N}{mm^2}$)	normal stress
τ	($\frac{N}{mm^2}$)	shear stress
ε	(-)	strain/extension
γ	(-)	shear angle
ν	(-)	Poisson's coefficient

symbol	dimension	designation
E	$(\frac{N}{mm^2})$	modulus of elasticity
G	$(\frac{N}{mm^2})$	rigidity modulus
S	$(\frac{N}{mm^2})$	stress and strain, design value of the actions/influences
R	$(\frac{N}{mm^2})$	loadability, design value of the strength
R^n	$(\frac{N}{mm^2})$	standard value of the design strength
R^o	$(\frac{N}{mm^2})$	basic value of the design strength
γ_n	-	valency factor
γ_f	-	load factor
	-	combination factor
γ_{mo}	-	material factor
γ_m	-	adaptation factor
- superscripts (high indices)		
n	-	standard value
o	-	basic value
- subscripts (low indices)		
t	-	time
T	-	temperature
m	-	flexure/bending
tor	-	torsion
t	-	tension
c	-	compression
v	-	shear
E	-	Euler
crit	-	critical
inst	-	instable
x,y,z		in the direction of the axes or around the axes x,y,z
0		in parallel with the grain/fibre
90		perpendicularly to the grain/fibre

Table 2: Reliability Grades and Valency Factors acc. to /14/

Reliability grade	Consequences of exceeding a limit state of the load-carrying capacity	Consequences of exceeding a limit state of the usability	Buildings / structures	Valency factor γ_n 4)
I	High danger to human lives and very serious economic consequences	very serious impairment of the utilization, serious economic consequences	Safety-relevant structures in construction of nuclear power plants Dams/barrages Railway bridges Loadbearing structures of theatres, cinemas, schools, railway stations, grandstands of sports facilities and other buildings/structures in which crowds are frequent Loadbearing structures of museums containing irretrievable treasures	1.0 1) 1.1 2)
II	Danger to human lives and/or considerable economic consequences	Impairment of the utilization, considerable economic consequences	Residential buildings, public and social buildings, industrial buildings as far as not included in reliability grade III Central warehouse and storage buildings for the population's supply, for technical equipment of great value and the like	1.0 1)
III	No danger to human lives and insignificant economic consequences	Insignificant impairment of the utilization, insignificant economic consequences, easy repairability	Warehouse and storage buildings for commercial products/goods, fertilizers, building materials, chemicals and the like Greenhouses, lighting columns/masts Structural units/components of secondary importance and insignificant consequences in case of failure even if the total building/structure is included in the reliability grades I or II	0. 1) 0. 3)

1) Is applicable in case of limit states with the occurrence of the failure state being announced in advance.
2) For safety-relevant structures in the construction of nuclear power plants.
3) If the period of utilization is < 5 years.
4) In case of limit states with a sudden failure not being announced in advance, $\Delta\gamma_n$ is to be increased by the amount $< \gamma_n = 0.05$

T a b l e 3 : Combination Factor acc. to /15/		
Load combinations	Number of the short-term loads	ψ
Basic combination[1)]	1	1.0
	2 or 3	0.9
	>3	0.8
Special combination [2)]	$\geqq 1$	0.8

1) maximum load, without sudden load
2) maximum load, including sudden load

T a b l e 4 : Load Factors acc. to /15/ [2)]		
Type of load	Load factors γ_f [1)]	
Dead load	1.1	0.9[2)]
Live load	1.4[3)]	

1) Are applicable only to the limit state of the load-carrying capacity.
   For the limit state of the usability, γ_f = 1.0 if there should not be any specific regulations.
2) Is to be applied if the reduction of the loading should have an unfavourable effect.
3) Other values can be found in /15/.

Table 5: Coefficients of correlation between sorting criteria and strength properties, determined with boards and planks made of European pine wood acc. to /13/

	Sorting parameter	Correlation with flexural strength R_m	Correlation with tensile strength R_t	Correlation with compressive strength R_c
1	Visual sorting acc. to DIN 4074	0.5	0.6	0.4
2	Volume weight (specific bulk gravity)	0.5	0.5	0.6
3	Annual ring width	0.4	0.5	0.5
4	Knottiness	0.5	0.6	0.4
5	Grain deviation	0.2	0.2	0.1
6	Modulus of bending elasticity E_m	0.7-0.8	0.7-0.8	0.7-0.8
7	Volume weight and knottiness	0.7-0.8	0.7-0.8	0.7-0.8
8	Modulus E_m and volume weight	0.7-0.8	0.7-0.8	0.7-0.8
9	Modulus E_m and knottiness	0.8	0.8	0.8

Table 6: Synopsis on single factors and their significance in the material factor

Single factor of $\gamma_{m,o}$	Significance of the partial safety factor
$\gamma_{m,o,1}$	Takes the uncertainty in the determination of the material parameters (between tested material and building construction) into consideration
$\gamma_{m,o,2}$	Takes the uncertainty in the design model caused by material or geometry parameters, but also by material-dependent influences into consideration
$\gamma_{m,o,3}$	Takes the efficiency of the check performed during the manufacture into consideration

Table 7: Standard Values of the Design Strengths and of the Modulus of Bending Elasticity E_m for Structural Timber and Glued Laminated Timber $\left(R^n_{(0.05)} = f_{k(0.05)}\right)$

loading/stress and strain		softwood (spruce/fir, pine, larch)										hardwood (stalk oak) (sessile oak) (red beech)
		structural sawn timber			glued laminated timber						round timber	
		quality grade acc. to TGL			strength grade							
		I	II	III	1	2	3	4 [1]	5 [1]	6 [1]		
Flexure/bending	$E_{m,50\%}$	11500	10000	9000	12500	11000	11000				12000	13000
	$E_{m,5\%}$	8200	7100	6500	9000	7100	7100				8500	9000
	R_m	24	22.0	19.0	34	26	26				26.5	40.0
Tension	$R_{t,0}$	16.0	14.5	12.0	22.5	17.0	17.0				14.5	24.0
	$R_{t,90}$	0.5	0.4	0.3	0.5	0.4	0.3				0.40	0.6
Compression	$R_{c,0}$	21.5	20.0	18.0	30.5	23.5	23.5				22.8	30.0
	$R_{c,90}$	8.0	7.0	6.0	11.5	8.0	8.0				7.0	10.0
Shearing-off	$R_{v,0}$	2.5	2.25	2.0	3.0	2.50	2.5				2.50	5.0
Shear force from lateral force	$R_{v,90}$	3.3	3.0	2.7	4.0	3.25	2.25				3.25	6.7

1) Layers of boards are being sorted mechanically; strength values will be available only in 1987.

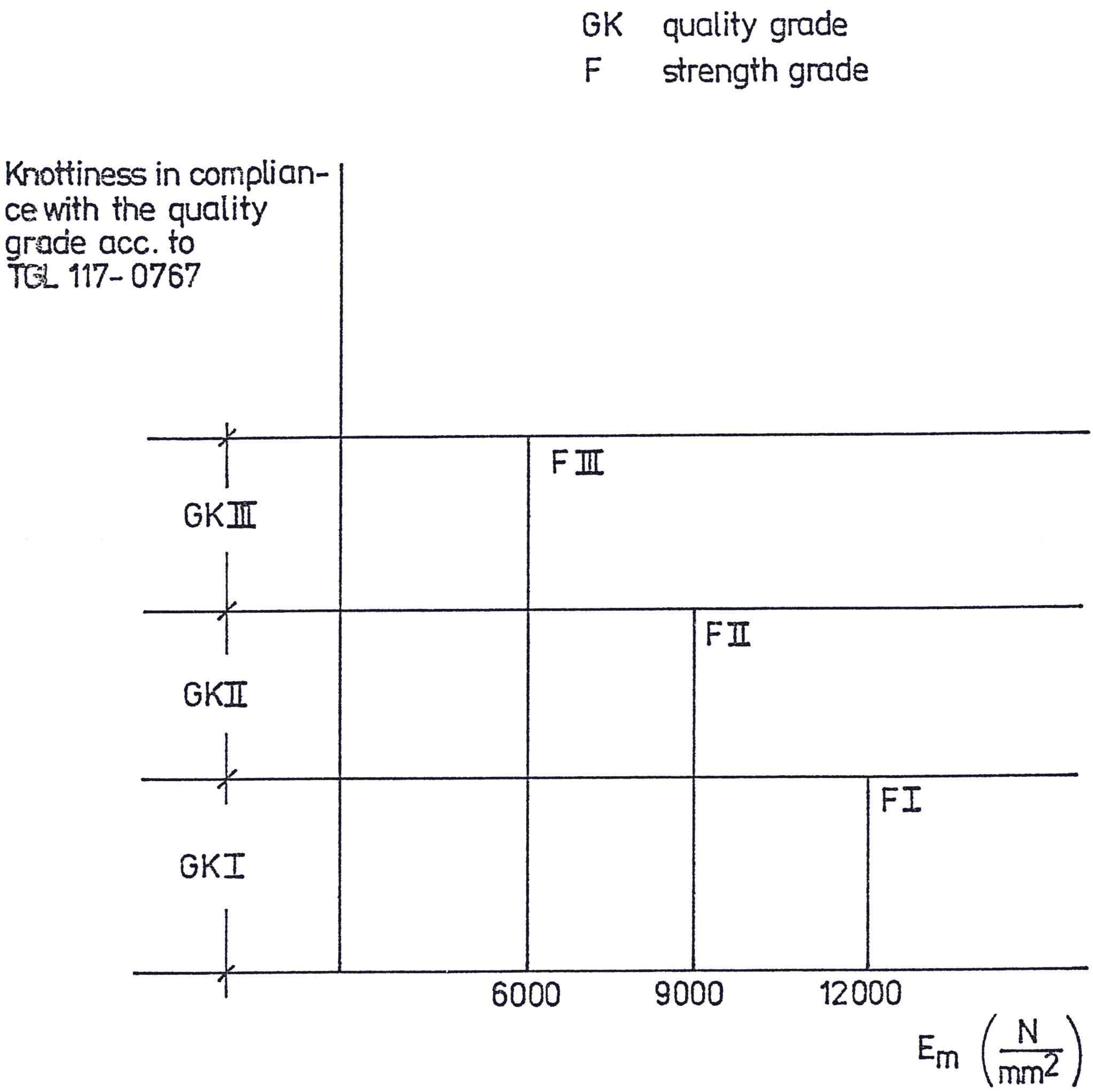


Figure 1: Strength grades of structural timber or layers of glued laminated timber.

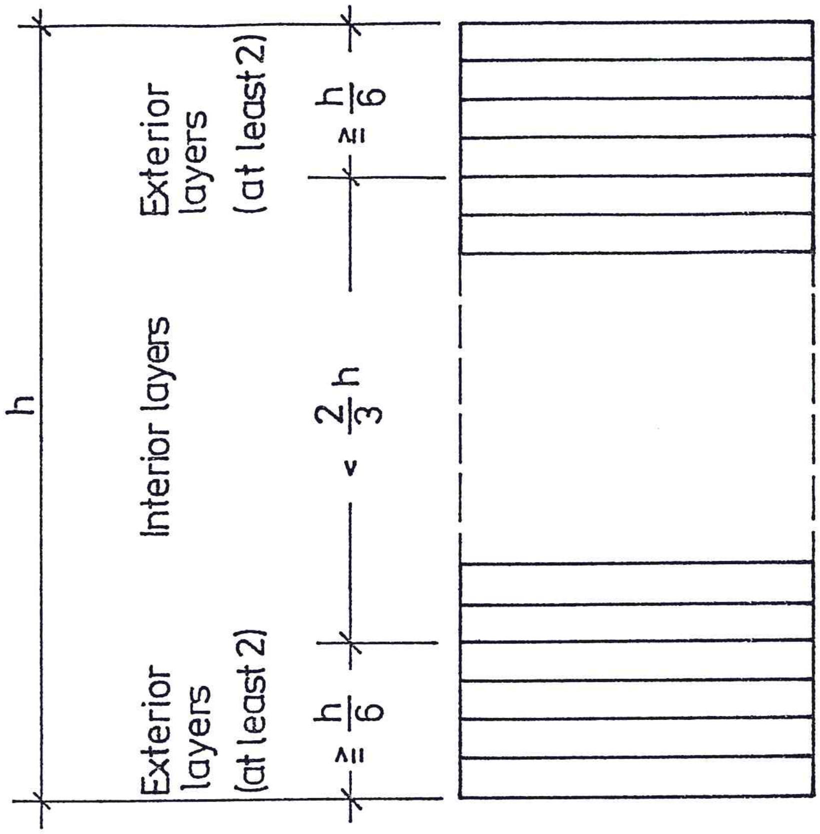


Figure 2: Design of the glued laminated timber

Table 8: Design of the new grades of glued laminated timber							
design		BSH 1	BSH 2	BSH 3	BSH 4	BSH 5	BSH 6
sorting of the layers		visually	visually	visually	machine	machine	machine
exterior layers	kind of timber	NSH GK I,II	NSH GK II	NSH GK I,II	NSH F I	NSH F II	NSH F II
	KZV(mm)	≧ 250	≧ 250	≧ 0	≧ 250	≧ 250	≧ 250
interior layers	kind of timber	NSH GK I,II	NSH GK III	NSH GK I,II	NSH F III	NSH F III	NSH F II
	KZV(mm)	≧ 250	≧ 0	≧ 0	≧ 0	≧ 0	≧ 0

KZV finger joints staggering
BSH glued laminated timber
NSH sawntimber – scots pine, sitka spruce, or larch
GK quality grade; F – strength grade

Table 9a: Moisture Grades			
moisture grade (FK)	moisture of timber u (%)	case of application to structures made of structural timber or glued laminated timber	K_e
FK 1	$\leqq$ 18	enclosed buildings/structures with and without heating, enclosed ventilated animal shelter buildings without heating, open and partially open roofed-over buildings/structures	1.0
FK 2	18 > u $\leqq$ 24	free-standing loadbearing systems/members without any protection against climatic influences	0.93
FK 3	> 24	structures being subjected to an immediate influence/action of water	0.8

Table 9b: Time Grades		
time grade	duration of the load action	K_t
A	continuous and / or long-term	0.67
B	short-term	0.83
C	instantaneous	1.0

Table 9c: Load Combinations			
load combination	time grade		
	A	B	C
A + B	A $\geqq$ 85 %	A < 85 %	-
A + C	A $\geqq$ 85 %	-	A < 85 %
A + B + C	A $\geqq$ 85 %	C $\leqq$ 15 % A < 85 %	C > 15 %
A etc. is the load percentage of time grade A of the total load etc.			

Table 9d: Temperature Grades		
temperature grade (TK)	temperature range T (^oC)	K_T
TK 1	$\leqq 35$	1.0
TK 2	$> 35 < 100^oC$	0.85

Table 10: Adaptation Factor γ_{m1} "Long-Term Behaviour" for GZT Limit States						
time grade	moisture grade (FK)					
	FK 1		FK 2		FK 3	
	temperature grade (TK)					
	TK 1	TK 2	TK 1	TK 2	TK 1	TK 2
A	0.75	0.64	0.7	0.6	0.6	0.51
B	0.9	0.77	0.85	0.72	0.75	0.64
C	1.1	0.94	1	0.85	0.9	0.77

Table 11: Adaptation Factor γ_{m2} "Cross-Sectional Height" for GZT Limit States with Flexural Load		
cross-sectional height h (mm)	structural timber	glued laminated timber (BSH)
$\leqq 200$	1	1
$200 > h \leqq 300$	0.95	
$300 > h \leqq 500$	-	0.95
$500 > h \leqq 800$	-	0.9
$800 > h \leqq 1500$	-	0.85
> 1500	-	0.8
For BSH $h \geqq 300$ mm: $\gamma_m = \left(\frac{300}{h(mm)}\right)^{\frac{1}{9}}$		

Table 12: Adaptation Factor γ_{m3} "Curvature of Timber" for GZT Limit States

$\frac{h}{r}$	0	$2 \cdot 10^{-3}$	$4 \cdot 10^{-3}$	$6 \cdot 10^{-3}$	$8 \cdot 10^{-3}$	10^{-4}
γ_{m3}	1	0.92	0.83	0.76	0.68	0.6

r is the radius of curvature of the timber

h is the thickness of the timber or - in case of glued laminated timber - of one layer

Table 13a: Degree of Loading of Structural Timber and Glued Laminated Timber

degree of loading	aggressive action	example [1)]
B 1	none/very low	For FK 1 with 0.5-20mg of SO_2 in $1m^3$ ai:
B 2	medium	For FK 1 with 20-100mg of SO_2 in $1m^3$ ai:
B 3	high	For FK 2 with 100-500mg of SO_2 in $1m^3$ ai:

1) Other regulations are indicated in reference /6/.
FK - moisture degree

Table 13b: Adaptation Factor γ_{m4} "Aggressive Media" for GZT and GZN Limit States

degree of loading	γ_{m4}	remarks
B 1	1	
B 2	0.8	For boards, laths/battens, planks
	1	For square timber and BSH without protective/ preservation system
B 3	0.4 - 0.5	For boards, laths/battens, planks
	0.8	For square timber and BSH without protective/ preservation system
	0.9[1)] - 1[2)]	For square timber and BSH with protective/ preservation system (e.g. "Kombinal", tar epoxy resin)

GZT - limit state of the load-carrying capacity
GZN - limit state of the usability

1) in case of impregnation with oily preservatives such as, e.g. - "Kombinal TD"

2) In case of impregnation with highly efficient protective/ preservation systems such as tar epoxy resin.
In case of a continuous influence of high temperature, e.g. according to temperature grade II, a highly efficient temperature-resistant coat (e.g. of tar epoxy resin) must be applied.

Table 14: 1986 - 1988 Research Programme

Research task №	Research objective
F 1	Basic values for structural timber subjected to flexural and compressive loading/stress (buckling)
F 2	Adaptation factor "Long-term behaviour" for structural timber subjected to flexural and compressive loading/stress (buckling)
F 3	Adaptation factor "Aggressive media" for structural timber subjected to flexural load
F 4	Basic values for glued laminated timber subjected to flexural load
F 5	Adaptation factor "Long-term behaviour" for glued laminated timber subjected to flexural load
F 6	Adaptation factor "Cross-sectional height" for glued laminated timber subjected to flexural load
F 7	Adaptation factor "Moisture of timber" for glued laminated timber subjected to flexural load
F 8	Basic values for the nailed connection with nails sized 3.4 x 90, subjected to shear stress/load
F 9	Basic values for the screwed connection with hexagonal wood screws sized 8 x 90, subjected to shear stress/load
F 10	Basic values for the dowelled connection with "KRD A80"-type key ring dowels subjected to shear stress/load

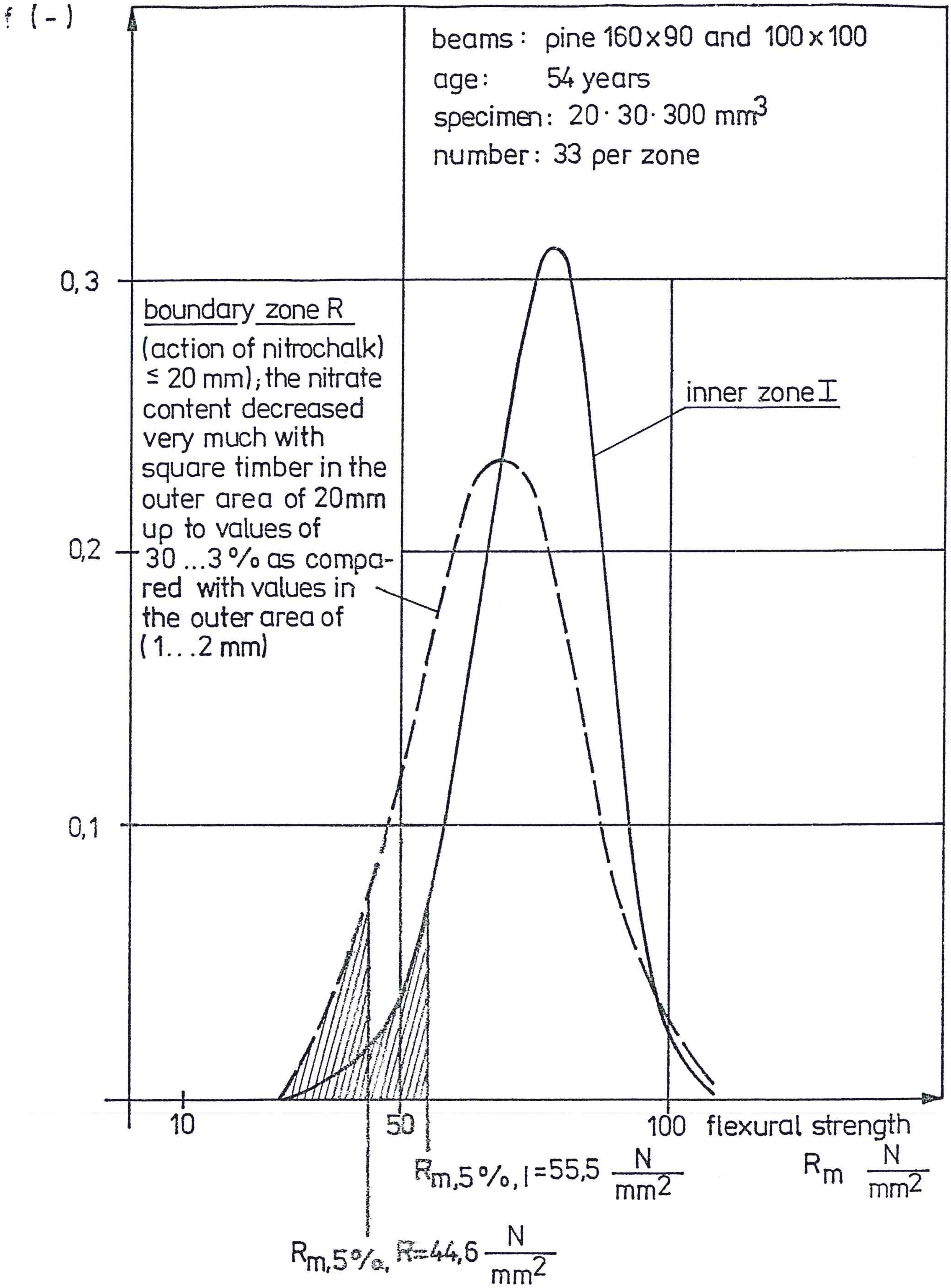


Figure 3 : Weibull distributions of the flexural strength of old timber