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INTERNATIONAL COUNCIL FOR BUILDING RESEARCH STUDIES AND DOCUMENTATION

WORKING COMMISSION W18A - TIMBER STRUCTURES

RELIABILITY-THEORETICAL INVESTIGATION INTO TIMBER COMPONENTS

A proposal for a supplement of the design concept

by

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MEETING TWENTY - TWO

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1. Introduction

Structural components made of timber are being designed by adopting the hitherto prevailing admissible stress method /9/ and the limit states method.
The design according to the limit states method has been accomplished in compliance with the draft of the new GDR Code (TGL 33 135/04 E 89; see /1/) which was largely approximated to the Eurocode 5, E. 10/87 (see /2/).
The components designed by adopting the above-mentioned methods have been subjected to a reliability-theoretical analysis. The calculation (design) covered the safety index β.

2. Dimensioning of the components

The studies and investigations are being carried out by using three components made of quality grade (GK) II sawn coniferous timber (NSH) with the strength grade C 5 according to /2/ which are being exposed to different types of stressing (loading); they are being designed by applying the admissible stress method and the limit states method (see Figure 2).
The calculation is being performed according to /9/ and /1/ for two girders subjected to bending and one eccentrically loaded compression member. The applied characteristic actions (dead load g_k, use load p_k, snow load s_k, wind load w_k), load factors γ and combination factors Ψ can be seen in Figure 3.
The characteristic actions are being applied with both the admissible stress method and the limit states method.
When designing the components by means of the limit states method, the factors being selected are $\gamma_M = 1.4$ as the material factor and $K_{mod,1} = 0.9$ as the modification factor concerning the "period of action". The characteristic values of the strength (characteristic indices are 5%-fractiles from test data obtained with the application of the 3-parametric Weibull distribution) and of the modulus of elasticity can be drawn from Figure 1 for quality grade II sawn coniferous timber (NSH GK II).

Figure 4 includes the check requirements (conditions) and the percentages of utilization of the admissible stresses and of the design values of the strengths for the two design methods. One can see the small consumption of timber when applying the limit states method in the case of the individual examples A and B (girders subjected to bending !). With the example C (flexural compression member !), no economic advantage resulting from the application of the limit states method can be determined.

3. Result of the reliability-theoretical investigations

The components indicated in Figure 2 are being subjected to a reliability-theoretical investigation which is being accomplished according to the first-order reliability theory.

The investigation into the influence of the random scatterings of loads and strengths on the safety and reliability of a load-bearing system is the content of the reliability theory.

In this connection, the prevailing safety level is characterized by the safety index β or an equivalent operative failure probability P_f (see Figure 5). In the reliability theory, loads and strengths are being represented as random (accidental) quantities X_i +). Subject to the accident, a random quantity can adopt various values.
Figure 5 shows distribution densities f (X_i) and the limit state equation for two transformed random quantities X_i.
Up to 7 random quantities are being applied in the calculation and design of the components.
Thus, a 7-dimensional space is available in which each random quantity X_i with its distribution function and distribution density are distributed at random.

The first-order reliability theory is characterized by the fact that in the design point $\hat{P}^*$ (see Figure 5) the distribution

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+) In the authors' instance, the random quantities X_i are as follows: g, p_1, p_2, s, q, c, f (see Figure 7).

functions of the random quantities are being approximated by normal distributions.
The calculation procedure is the content of the "Beta 10" computer program (see Figure 6).
By means of said program, approximate values of β and P_f are being computed for an arbitrary limit state with stochastically independent random quantities which (i.e. the limit state) is to be entered as a special subprogram. Various distribution functions (normal distribution NV, Weibull distribution WV, logarithmic normal distribution LNV and others) can be taken into consideration.
The program is computing the failure probability according to the normal tail approximation.
The distribution densities of the loads are being drawn from /5/ taking into account /6/ (see Figure 7).
The distribution densities of the strengths are being determined according to /7/ (see Figure 7).
The conversion of the loads into stresses is being accomplished by means of the cross-sectional values which are resulting from the dimensioning (design) for σ_k = zul σ (admissible stress method) and for $\sigma_d = f_d$ +) (limit states method).
The limit state equation (see Figure 5) $\hat{g} = \hat{f} - \hat{\sigma}$ will be prepared for each component and includes up to 7 random quantities (see Figure 8)

The reliability-theoretical design (calculation) produced the following results:

(a) The amount of the safety index β is in the case of the design cross section for σ_k = zul σ :
β = 2.5 up to 4.7 (see Figure 9)
and for $\sigma_d = f_d$:
β = 2.5 up to 3.5 (see Figure 9).

+) σ_k is the stress from the characteristic values of the loads
σ_d is the stress from the design values of the loads
f_d is the design value of the strength

One can see, that the safety index required for all construction methods $_{erf}\beta \geqq 3.5$ of the reliability grade III according to /8/ is lower with part of the investigated timber components.

The safety level for the design (dimensioning) of $\sigma_d = f_d$ (limit states method) is below that of the design of $\sigma_k = {}_{zul}\sigma$ (admissible stress method).

Within the range of $\beta \leqq 3.5$, the shortfall amounts to 0 up to 19 % and is thus still justifiable.

(b) The amount of the failure probability P_f is in the case of the design cross section for $\sigma_k = {}_{zul}\sigma$:

$P_f = 0.001 \cdot 10^{-3}$ up to $6.3 \cdot 10^{-3}$ (see Figure 9)

and for $\sigma_d = f_d$:

$P_f = 0.3 \cdot 10^{-3}$ up to $6.1 \cdot 10^{-3}$ (see Figure 9).

One can see that the failure probability required for all construction methods $_{erf}P_f = 0.23 \cdot 10^{-3}$ of the reliability grade III according to /8/ is being exceeded with nearly all investigated timber components.

(c) The design cross section for $\sigma_d = f_d$ in compliance with the limit states method is based upon the material factor of $\gamma_M = 1.4$.

The results as shown in Figure 9 are largely dependent on the distribution densities of the loads. They are being revised at present. Thus, the results described hereinbefore are only initial orientation data.

4. Summary

The following three timber components are being investigated in terms of the reliability theory:

A) purlin of an industrial building
B) intermediate floor beam of an office building
C) wall frame post of an office building.

In this connection, the design cross sections from the check requirements (conditions) of $\sigma_k = {}_{zul}\sigma$ and $\sigma_d = f_d$ are being assumed.
The safety level prevailing with $\sigma_d = f_d$ (limit states method) is still justifiably below that prevailing with $\sigma_k = {}_{zul}\sigma$ (admissible stress method). The safety level for the admissible stress method is in the case of the investigated timber components in part lower than that of other construction methods. The results and findings cannot be generalized since only a few application examples are available.
With the distribution densities of the loads exercising a considerable influence on the results and findings, the same shall be regarded only for information and orientation purposes.

5. References

/1/ Industrial GDR Code Specification No. TGL 33 135/04 E 89
"Holzbau, Tragwerke, Berechnung, Bauliche Durchbildung"
(Timber construction; Loadbearing systems; Calculation; Structural design)
Draft, September 1989

/2/ Eurocode 5
"Holzbauwerke" - Deutsche Entwurfsfassung
(Timber structures - German draft wording)
October 1987

/3/ Forschungsbericht G 3 "Grenzzustände Holzbau"
(Research report G 3 "Limit states in timber construction")
Academy of Building of the GDR, Institute for Industrial Buildings - Berlin, November 1987

/4/ Kiesel, :
"Beitrag zur Ermittlung der Verteilungsfunktion der Festigkeitseigenschaften des Bauholzes unter besonderer Berücksichtigung des Festigkeitsverhaltens bei der Druckbeanspruchung für eine Bemessung nach der Methode der Grenzzustände"
(Paper on the determination of the distribution function of the strength properties of structural timber with particular consideration of the strength behaviour under compressive stress for a design by adopting the limit states method)
Wismar College of Technology; Research report G 4; Wismar, October 1987

/5/ Spaethe, G.:
"Die Sicherheit tragender Baukonstruktionen"
(The safety of loadbearing building constructions)
Published by: Verlag für Bauwesen - Berlin, 1987

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/6/ Steck, G.:
"Die Zuverlässigkeit des Vollholzbalkens unter reiner Biegung"
(The reliability of the solid timber beam subjected to pure bending)
Karlsruhe University; Dissertation (thesis), 1982

/7/ Freingruber, H.-Chr.:
"Anwendung des neuen Sicherheitskonzepts im Bereich des Holzbaues - Vorteile und Vergleich mit der bisherigen Bemessungspraxis Besonderheiten des Holzbaues"
(Application of the new safety concept in the field of timber construction - Advantages and comparison with the hitherto prevailing design practice as to particularities of timber construction)
Published in: ÖJAZ, 132th y., No. 9/1987; Vienna, 1987

/8/ Spaethe, G.:
"Zuverlässigkeitskonzeption für tragende Baukonstruktionen"
(Reliability conception for loadbearing building constructions)
Academy of Building of the GDR; Berlin, September 1986

/9/ Industrial GDR Code Specification No. TGL 33 135/01:
"Holzbau, Tragwerke, Berechnung, Bauliche Durchbildung"
(Timber construction; Loadbearing systems; Calculation; Structural design) - January 1984

/10/ Rug, W.; Badstube, M.; Kofent, W.:
New GDR Timber Design Code - State and Development
CIB W 18 Meeting Twenty-Two, Berlin/GDR

Stressing		Source	Coniferous timber					
			sawn structural timber			glued laminated timber		
			quality grade I	II	III	grade 1	2	3
			Strength grade acc. to Eurocode 5 /2/ C 6	C5	C3	C6	C5	C4
bending	$f_{m,k}$	test 1)	29,6	26,4	23,9	27,9	28,1	27,0
		Euroc. 2)	28,5	24	19	28,5	24	21,5
		specif.	28,5	24	19	28,8	24	21,5 5)
tension	$f_{t,o,k}$	test	22,7	13,1	7,1	---	---	---
		Euroc.	17	14,5	11,5	---	---	---
		specif.	17	14,5	7,1	---	---	---
tension on key-dove-tailed timber	$f_{t,o,k}$	test	---	14,4	---	---	---	---
		Euroc.	---	---	---	---	---	---
		specif.	---	14,4	---	14,4	4,8	14,4
compres-sion	$f_{c,o,k}$	test	22,3	20,4	18,5	---	---	---
		Euroc.	26	21,5	17,5	---	---	---
		specif.	24	21,5	17,5	24	22,3	24
bending	$E_{o,k}$	test	8600	7600	7200	10100	9700	9500
		Euroc.	8550	7440	6650	8550	7440	7095
		specif.	8500	7500	6500	8500	7500	8500
bending	$E_{o,mean}$	test	12300	11300	10500	11500	10800	11000
		Euroc.	12000	11000	9000	12000	11000	10000
		specif.	12000	11000	9000	12000	11000	10000

Figure 1: Characteritic values and mean values of the strength and of the modulus of elasticity, in N/mm^2

Footnotes to Fig. 1:

1) Values from test acc. to /3/ and /4/

2) Values from the Eurocode 5 acc. to /2/

3) Values from the TGL Gdr Code Specification acc. to /1/

4) Grades of glued laminated timber:

Grade 1: All layers consist of sawn coniferous timber (NSH) of the quality grade (GK) II.
The staggering between the Key-dovetail connections (KZV) is always = 250 mm

Grade 2: External layers within the range of $^1/_6$ of the girder depth consist of NSH GK II, internal layers of NSH GK III.
KZV = 250 mm is found only in the external layers.

Grade 3: All layerssconsist of NSH GK II with KZV = 0.

5) $f_{m,c,k} = 24 \frac{N}{mm^2}$

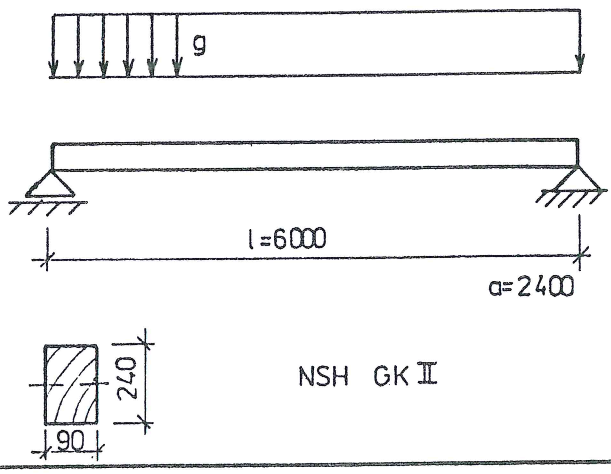
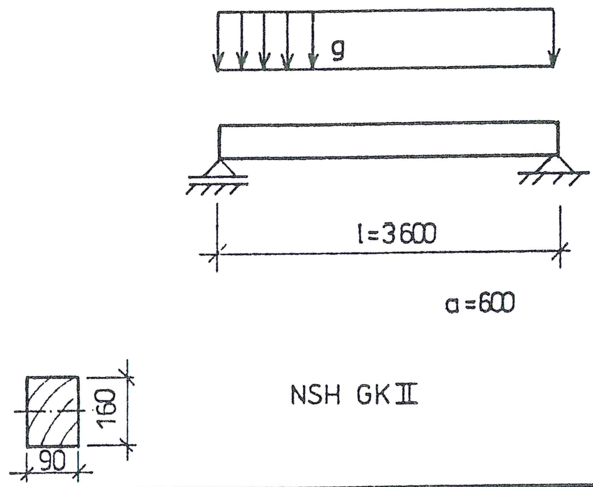
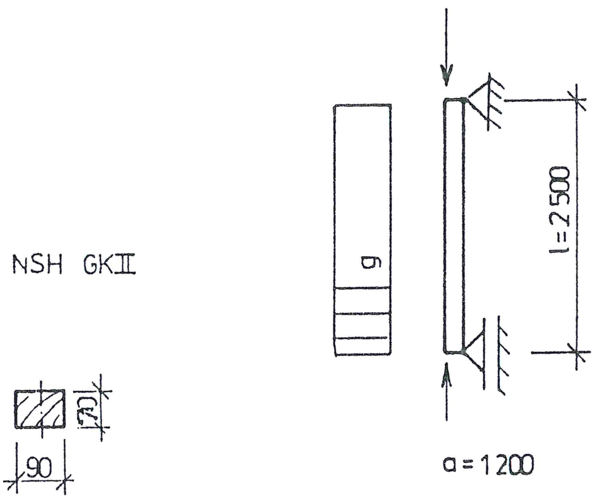
Example	Component	System
A	purlin of an industrial building	
B	intermediate floor beam of an office building	
C	wall frame post of an office building	

Figure 2: Application examples

Loading	Application example A	B	C
dead load	$g_K = 0{,}27 \frac{KN}{m^2}$ $\gamma = 1{,}1$	$g_K = 0{,}95 \frac{KN}{m^2}$ $\gamma = 1{,}1$	$g_K = 2{,}3 \frac{KN}{m^2}$ $\gamma = 1{,}1$
use load		$p_K = 2{,}75 \frac{KN}{m^2}$ $\gamma = 1{,}4$	$p_K = 2{,}75 \frac{KN}{m^2}$ $\gamma = 1{,}4$ $\psi = 0{,}9$
snow load	$s_K = k_s \cdot c \cdot s_{0,K}$ $= 1 \cdot 1 \cdot 0{,}5$ $= 0{,}5 \frac{KN}{m^2}$ $\gamma = 1{,}4$		$s_K = k_s \cdot c \cdot s_{0,K}$ $= 1{,}01 \cdot 0{,}63 \cdot 0,$ $= 0{,}445 \frac{KN}{m^2}$ $\gamma = 1{,}4$ $\psi = 0{,}9$
wind load			$w_K = c \cdot q_{0,K}$ $= 1 \cdot 0{,}55$ $= 0{,}55 \frac{KN}{m^2}$ $\gamma = 1{,}2$ $\psi = 0{,}9$

Combination of the actions in general:

$$S_d = \gamma_G \cdot G_K + \Sigma \psi_i \cdot \gamma_{Q,i} \cdot Q_{K,i}$$

with $G_K = g$ (here as related to the ground area)

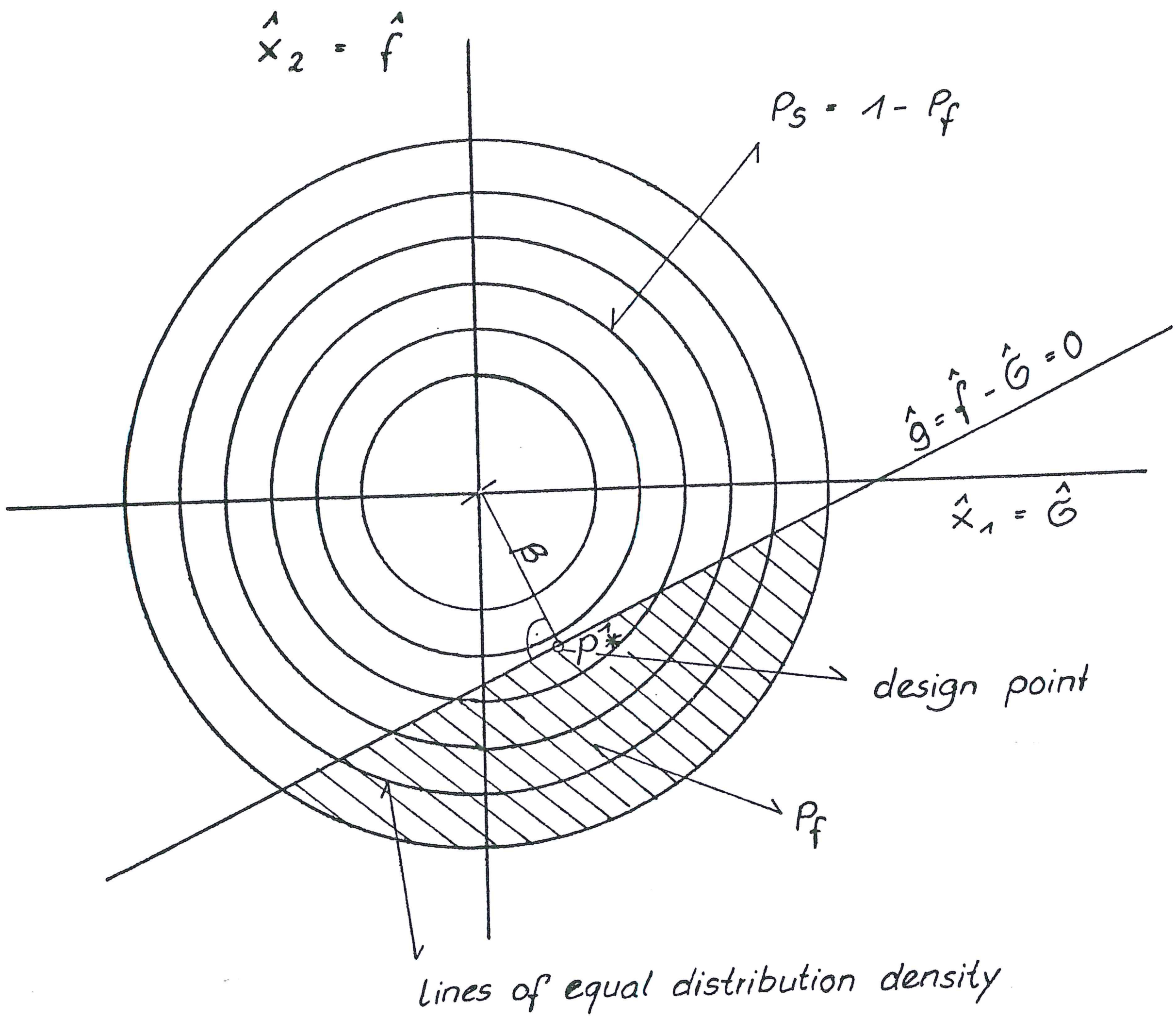
$Q_{K,i} = p_K, s_K, w_K$

Figure 3: Characteristic actions

Load and combination factors

Example	Admissible stress method acc. to /9/ — check requirement	utilization of admissible σ	Limit states method acc. to /1/ & /2/ — check requirement	utilization of admissible σ
A	$\sigma \leq$ admissible σ_m $9{,}6 < 10 \ \frac{N}{mm^2}$	96%	$\sigma_d \leq f_{m,d}$ $12{,}5 < 15{,}4 \ \frac{N}{mm^2}$	81%
B	$\sigma \leq$ admissible σ_m $9{,}4 < 10 \ \frac{N}{mm^2}$	94%	$\sigma_d \leq f_{m,d}$ $12{,}4 < 15{,}4 \ \frac{N}{mm^2}$	80,5%
C	$\omega \cdot \sigma_c + \frac{\text{admissible } \sigma_{c,0}}{\text{admissible } \sigma_m} \cdot \sigma_m$ $\leq$ admissible $\sigma_{c,0}$ $5{,}6 + 4{,}3 = 9{,}9$ $< 10 \ \frac{N}{mm^2}$	99%	$\frac{1}{K_c} \cdot \sigma_{c,d} + \frac{1}{K_m} \cdot \frac{f_{c,0,d}}{f_{m,d}} \cdot$ $\cdot \sigma_{m,d} \leq f_{c,0,d}$ $7{,}9 + 5{,}8 = 13{,}7$ $< 13{,}8 \ \frac{N}{mm^2}$	99%

Figure 4 : Check requirements



Meanings:

P_s probability of survival

$\hat{\sigma}$ transformed random quantity of the stress

$$\hat{\sigma} = \frac{\sigma - \sigma_{mean}}{s_\sigma} \; ; \qquad s_\sigma \text{ standard deviation}$$

s_{mean} mean value

$\hat{f}$ transformed random quantity of the strength

$$\hat{f} = \frac{f - f_{mean}}{s_f} \; ; \qquad s_f \text{ standard deviation}$$

f_{mean} mean value

β safety index $\qquad \beta = \dfrac{f_{mean} - \sigma_{mean}}{\sqrt{s_f^2 + s_\sigma^2}}$

Figure 5: Representation of the safety index β and of the failure probability P_f for 2 random quantities.

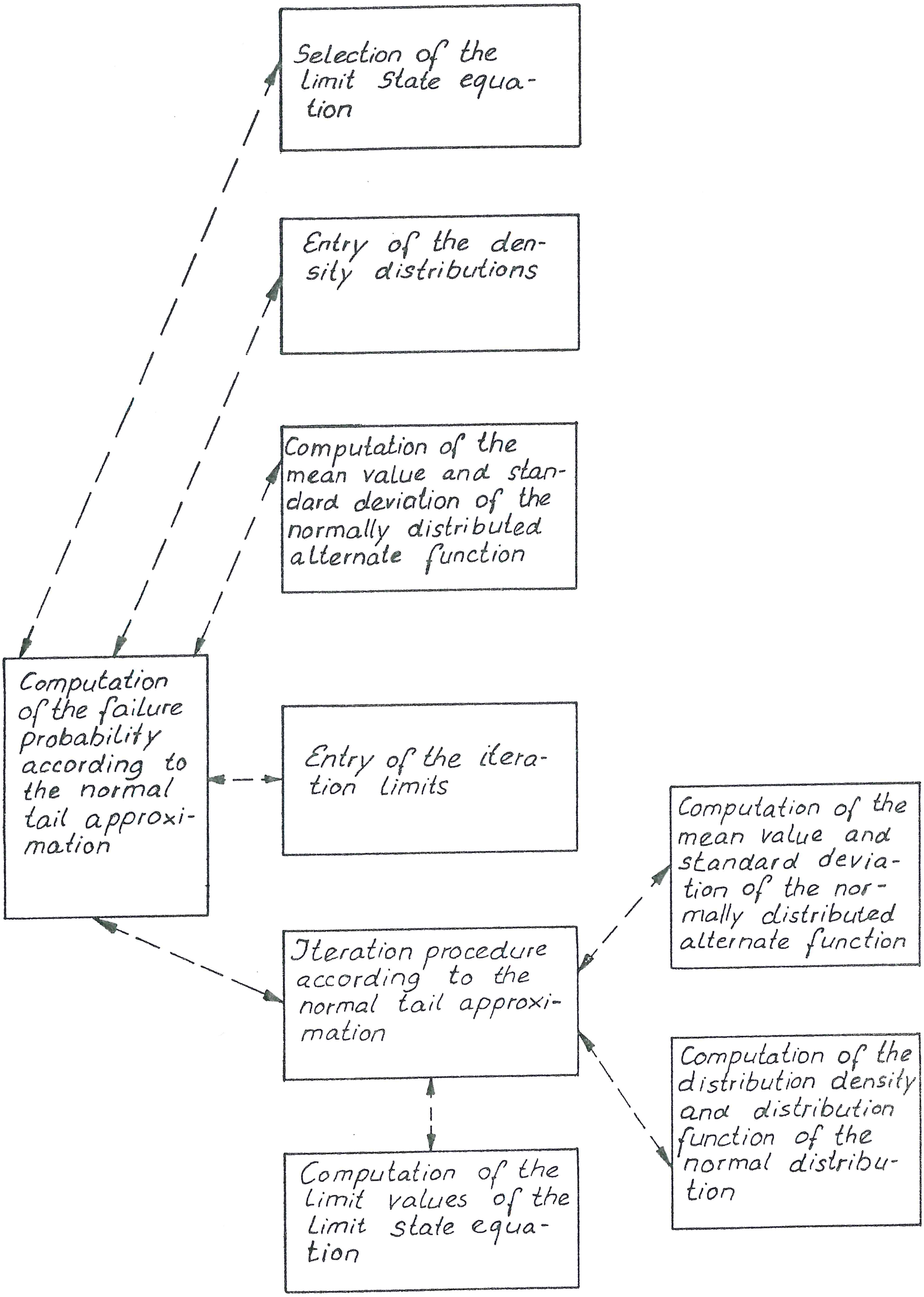


Figure 6: "Beta 10" computer program

Program structure

Random quantity	Application example A	B	C
dead load	$g_{mean} = 0{,}27 \frac{KN}{m^2}$ $v_g = 0{,}1$	$g_{mean} = 1{,}7 \frac{KN}{m^2}$ $v_g = 0{,}1$	$g_{mean} = 2{,}17 \frac{KN}{m^2}$ $v_g = 0{,}1$
long - time use load		$p_{1,mean} = 0{,}75 \frac{KN}{m^2}$ $v_{p_1} = 0{,}47$	$p_{1,mean} = 0{,}75 \frac{KN}{m^2}$ $v_{p_1} = 0{,}47$
short - time use load		$p_{2,mean} = 1{,}24 \frac{KN}{m^2}$ $v_{p_2} = 0{,}9$	$p_{2,mean} = 1{,}24 \frac{KN}{m^2}$ $v_{p_2} = 0{,}9$
snow load	$s_{mean} = 0{,}5 \frac{KN}{m^2}$ $v_s = 0{,}2$		$s_{mean} = 0{,}5 \frac{KN}{m^2}$ $v_s = 0{,}2$
dynamic pressure			$q_{mean} = 0{,}738 \frac{KN}{m^2}$ $v_q = 0{,}21$
aerodynamic coefficient			$c_{mean} = 1$ $v_c = 0{,}1$
strength	$f_{m,mean} = 37 \frac{N}{mm^2}$ $v_f = 0{,}27$ $k_{mod,1} = 0{,}9$	$f_{m,mean} = 37 \frac{N}{mm^2}$ $v_f = 0{,}27$ $k_{mod,1} = 0{,}9$	$f_{c,0,mean} = 32 \frac{N}{mm^2}$ $v_f = 0{,}18$ $k_{mod,1} = 0{,}9$

Meanings:

x_{mean} = mean value , v_x = variation coefficient

Figure 7: Distribution densities of the loads and strengths

Example	Limit state equation
A	$g = f_m \cdot K_{mod,1} - (\sigma_{m,g} + \sigma_{m,s})$
B	$g = f_m \cdot K_{mod,1} - (\sigma_{m,g} + \sigma_{m,p1} + \sigma_{m,p2})$
C	$g = f_{c,0} \cdot K_{mod,1} - (\sigma_{c,0,g} + \sigma_{c,0,p1} + \sigma_{c,0,p2} + \sigma_{c,0,s} + \sigma_{m,w} \cdot c)$

Meanings:

f = Distribution density of the strength. The distribution density is characterized by the mean value and variation coeffizient (see Figure 7).

σ = Distribution density of the stress due to the loads g, p_1, p_2, s, w (see Figure 7).

c = Distribution density of the aerodynamic coeffizient.

Figure 8: Limit state equations

Example	Number of the random quantities	Design cross section for σ_K = admissible σ:		Design cross section for $\sigma_d = f_d$:	
		β (-)	P_f (-)	β (-)	P_f (-)
A	3	4,7	$0{,}001 \cdot 10^{-3}$	3,45	$0{,}28 \cdot 10^{-3}$
B	4	3,15	$0{,}829 \cdot 10^{-3}$	2,64	$4{,}19 \cdot 10^{-3}$
C	7	2,5	$6{,}26 \cdot 10^{-3}$	2,51	$6{,}06 \cdot 10^{-3}$

Figure 9: Calculated values of the safety index β and of the failure probability P_f.

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