MATERIAL BEHAVIOUR AND STABILITY IN
ALUMINIUM-CONSTRUCTION (E DIN 4113)

Otto Steinhardt
Prof. of Civil Engineering
University (T. H.) Karlsruhe
W.-Germany

ABSTRACT

KEY WORDS:

Alloy-Materials, General Buckling of Struts, Standardisation

Overall buckling by bending and torsional flexural buckling of aluminium alloys can be understood by a set of two formulae, beyond this frame-buckling is cleared up.

Introduction

The up-to-date standard-specifications for compressed mem-
bers in aluminiumconstruction should reasonably follow the
example of s t e e l - construction standardisations.
There, the correlations and interrelations between material,
section-groups and "imperfections" lead to relastistic ge-
neral definitions and formulations for "planned-centrical"
(but not yet expressly for "excentrical") loaded struts -
as H e r m a n n B e e r , his collaborators and others
demonstrated in a clear and remarkable manner. The funda-
metal buckling-curves (_fig. 1_, overall buckling with ex-
cessive bending) offer the collape-stress d_S (basic-column-
stress) for a given slenderness ratio (probable values,
each with a tolerance limit equal 2,3 % of collapse load
F_S, found by more than one thousand special tests). -
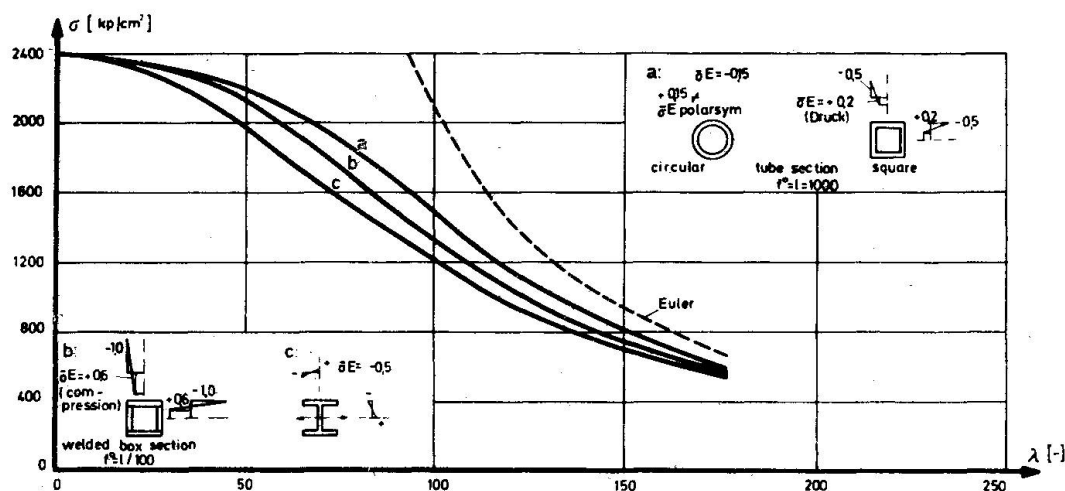
Fig. 1
**European Curves of the Basic -Column -Strength
included initial imperfections and residual stresses
(Steel St37)**

Here, with regard to _aluminiumconstructions_ (and specially
to the E DIN 4113, 1973) one should differentiate (accor-
ding to six basic alloys), on the one hand between peculiar
and disproportionate d,ϵ-curves (each of them very suffi-
ciently described as a tripartite-polygon); on the other
hand there are no residual stresses in not-welded and ma-
trix-pressed sections (_fig. 2_). -

Additionally, it may be noted that it seems possible to
conceive the behaviour of compressed steel-struts, even
with residual stresses, by a method which will be explai-
ned in the following: For instance, a s t e e l - strut

194

with only geometrical imperfections according to u = i$(\lambda/320)^2$ (material St. 37, σ_y = 2,4 Mp/cm^2, n = 3,15, μ = 0,575) is computable very accurately (for the case fig. 1.a) if the formula of fig. 3 is taken as a basis; hereby the greatest deviation from the Beer-curve may be only 2 to 4 %. -

The Standardisation

In the new E DIN 4113 (in chapter 8.1) the σ-ϵ-(compression) diagram of each alloy will be replaced by a tripartite polygon: At first for flexural buckling it turned out that the exact (computer-)analysis of the elastic-plastic collapse stress σ_S, for single and double symmetrical cross sections over the whole range of slenderness up to λ = 1/i = 250 produces results not more than 2 or 3 percent higher than given by the formulae (a) and (b) (see figure 3). -

a.

b.

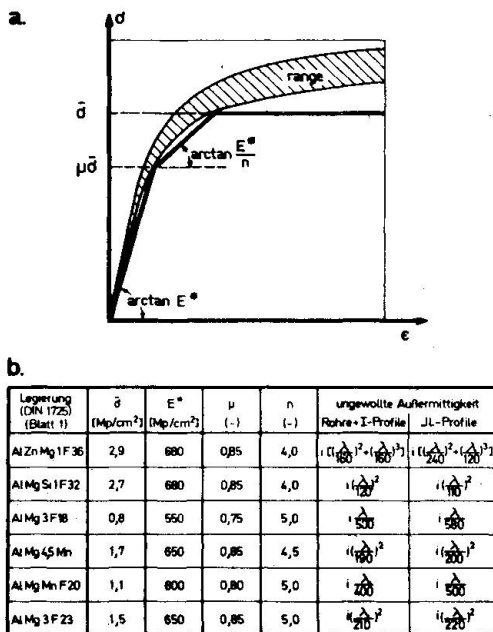| Legierung (DIN 1725) (Blatt 1)	σ [Mp/cm^2]	E* [Mp/cm^2]	μ (-)	n (-)	ungewollte Außermittigkeit Rohre+I-Profile	JL-Profile
AlZnMg1F36	2,9	680	0,85	4,0	$i\left[\left(\tfrac{\lambda}{160}\right)^2+\left(\tfrac{\lambda}{160}\right)^3\right]$	$i\left[\left(\tfrac{\lambda}{240}\right)^2+\left(\tfrac{\lambda}{120}\right)^3\right]$
AlMgSi1F32	2,7	680	0,85	4,0	$i\left(\tfrac{\lambda}{120}\right)^2$	$i\left(\tfrac{\lambda}{110}\right)^2$
AlMg3F18	0,8	550	0,75	5,0	$i\tfrac{\lambda}{500}$	$i\tfrac{\lambda}{580}$
AlMg4,5Mn	1,7	650	0,86	4,5	$i\left(\tfrac{\lambda}{190}\right)^2$	$i\left(\tfrac{\lambda}{200}\right)^2$
AlMgMnF20	1,1	800	0,80	5,0	$i\tfrac{\lambda}{200}$	$i\tfrac{\lambda}{500}$
AlMg3F23	1,5	650	0,86	5,0	$i\left(\tfrac{\lambda}{210}\right)^2$	$i\left(\tfrac{\lambda}{220}\right)^2$

Fig. 2 a. Tripartite σ,ϵ-Polygon (Aluminium)
b. Characteristic alloy values

$$\frac{N_v}{\mu\bar{N}} + \frac{M_v}{(1-\frac{N_v}{N^*})\mu M^*} \leq 1 \quad (a)$$

$$\psi\frac{N_v}{\bar{N}} + \frac{M_v}{(1-\frac{N_v}{N^*})\cdot M^*} \leq 1 \quad (b)$$

$$\frac{n+1}{2} \quad \frac{N_v}{N^*}\begin{cases}>1 \text{ formula (a)}\\<1 \text{ formula (b)}\end{cases} \quad (c)$$

$$\psi = 1 + \frac{n-1}{2}(1-\mu)\ \frac{\bar{N}}{N^*-N_v}$$

N^*=the smaller value of $\begin{cases}\frac{\pi^2 E^* F}{\lambda^2} & \text{(Euler)}\\ \frac{\pi^2 E^* F}{\lambda^2_v} & \text{(DIN 4114, Ri 10.13)}\end{cases}$

M^*=the smaller value of $\begin{cases}M_{pl} = \gamma\ \bar{\sigma}\ W_o\text{(plastic bending moment)}\\ M_{KI} \quad \text{(Lit. Kollbrunner-Meister)}\end{cases}$

$N_v = v\cdot N$, $M_v = v\cdot\left[A_m|M_2|+|N_{vorh}|\cdot u\right]$

$A_m = \frac{0,6+0,4 M_2/M_1 \geq 0,4}{(0,85}$ $\quad$ fixed bearing (not fixed bearing)

v = safety factor

Fig. 3 Formulas (a)(b)and(c) for the Design of Compressed Columns

For the six most important aluminium-alloys, the decisive polygon was shown above in figure 2, (their characteristic dimensions E, σ, n andμ are tabulated). The tripartite polygon is found as the lower limitation of a "bunchy despersion" of many experimentally determined σ-ϵ diagrams).

195

The new standard will contain additionally (in chapter 8.2)
a series of ω -tables; therefore it will also be possible
in future to use (selectively) the so called "ω-procedure".
Those ω -tables (according to the DIN 4114, 1952) consider
- for the case of the exactly planned-centrical loaded
strut - only partly the unavoidable geometric imperfec-
tions $u = i/20 + 1/500$; therefore, the greater range of
slenderness is determined by an eigen-value analysis and
here the buckling factor grows up to $v_{Ki} = 2,5$.

The new E DIN 4113 is principally based on the excentrical-
ly loaded strut; by the way, it is connected in parallel to
the "ω-procedure" by functions $u = f(\lambda)$ (found by attemp-
ting) which result in such collapse stresses $\sigma_S = P_u/F$ that
$\sigma_S / v_S = \sigma_{d\,zul}$. Now it is essential to state that v_K is
constant over all slenderness ratios. That means that "sa-
fety factors" (know from the DIN 4114) v_{ki}, v_K and v_{kr} can
be replaced by only   o n e   value. -

How far does it seem possible for each case in point to
start exclusively from the determined geometric "imperfec-
tions" and from the σ-ϵ- polygon? In addition to this the
following may be declared up to the present: In causes of
flexural bending, there is not only the simple "ω-procedu-
re" to be replaced (for the planned-centrical strut!) by
the formulae given in figure 3, but there result clear σ_S-
values also for the excentrically loaded ones; more presi-
cely, there result the relations regulating the forces and
moments N and M, according to the formulae (a) to (c). -

The main advantage of the new thinking (not at all'an inter-
national one, but in view of the German DIN 4114) seems to
be given by the fact that one may succeed in integrating al-
so the   t o r s i o n a l   flexural buckling (besides the
"over turning" and the "torsional buckling"). Therefore,the
"Karlsruher Formeln" were applied to some limiting cases,
partly delivering very clear deviations in comparison with
the "theoretical" values of the DIN 4114. On the basis of
many calculations and also in borderline cases (this is
done in the dissertation of F. Labib, 1972/73), the above
mentioned formulae could be estimated as very useful; but
additionally a suitable series of tests should verify the
real circumstances.

Some aluminium-specimens (fig. 4) were carefully produced
(partly with stress relieving by annealing), and the σ-ϵ-
compression-diagrams (as well as generally the σ-ϵ tension-
diagrams) were registered. Though (see specimen No. 1 to
No. 3) a relatively weak aluminium alloy lying outside the
new standard, was investigated, it seems to be suited for
recording sensitively the aim which should be followed here.

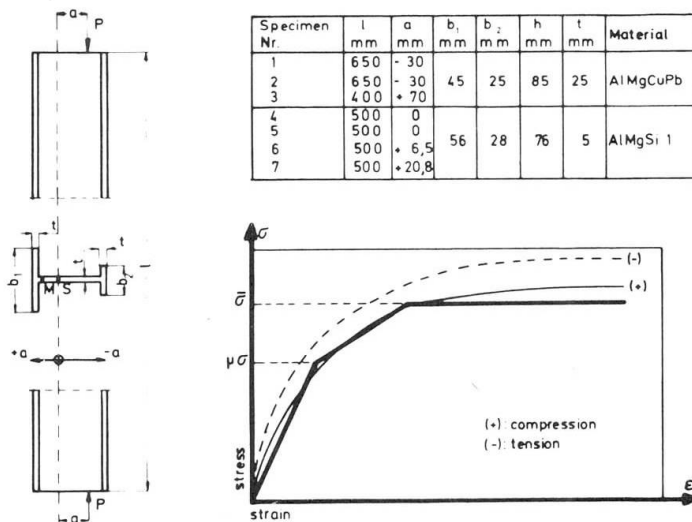| Specimen Nr.	l mm	a mm	b_1 mm	b_2 mm	h mm	t mm	Material
1	650	- 30					
2	650	- 30	45	25	85	25	AlMgCuPb
3	400	+ 70					
4	500	0					
5	500	0	56	28	76	5	AlMgSi 1
6	500	+ 6,5					
7	500	+ 20,8					

(+): compression
(-): tension

Fig. 4   Investigations on Torsional Flexural Buckling Specimens
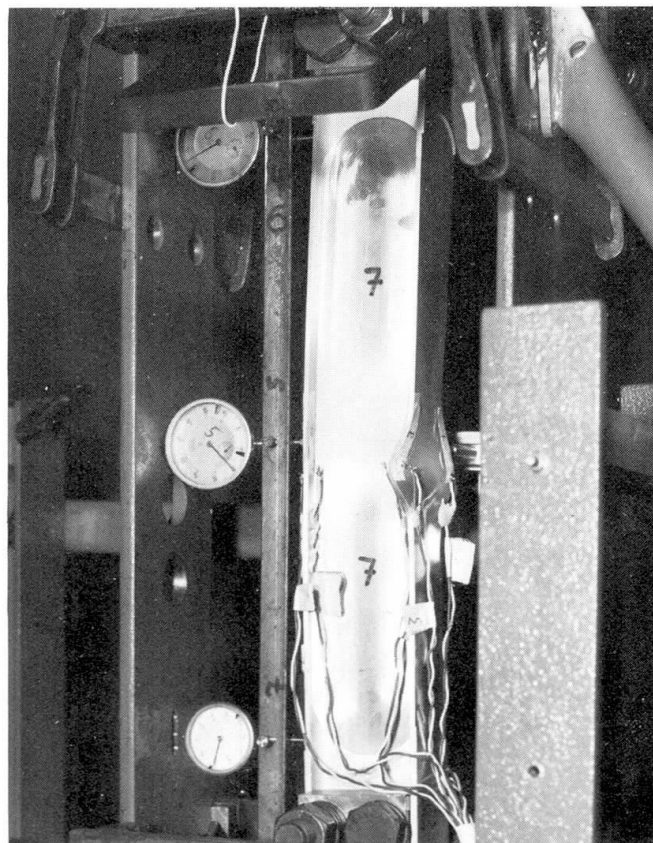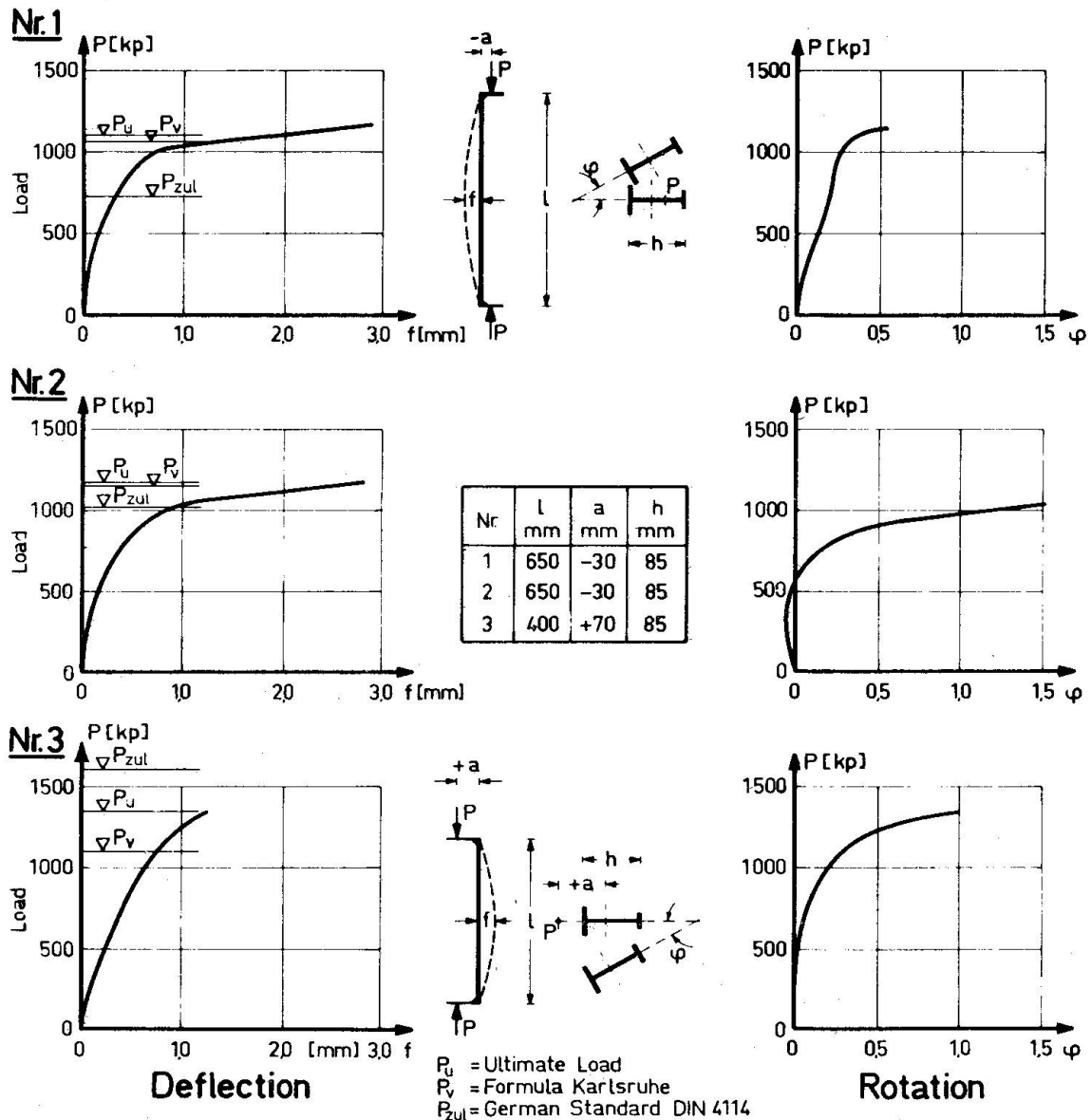

Fig. 5   Setup for Buckling Tests

A photograph (fig. 5) shows the total mode of the test procedure as well as the normally used measuring instruments.

It was possible to watch permanently not only the strains but also the total and part torsions of the medium cross section of the strut and also the lateral deflections.

The ultimate loads of the tests No. 1 to No. 3 are compiled in figure 6. They are compared with the values appropriate

Nr	l mm	a mm	h mm
1	650	−30	85
2	650	−30	85
3	400	+70	85

P_u = Ultimate Load
P_v = Formula Karlsruhe
P_{zul} = German Standard DIN 4114

Fig. 6 **Load-Deformation-Curves of Aluminium Columns**
(Ultimat-Loads and Calculated-Forces)

to the "formulae" (in figure 3) and with the results according to DIN 4114 and they recommend these formulae as most realistic and accurate! At any rate they are very useful (for

198

Fig. 7 — Qualitative buckling load plots according to Formula Karlsruhe and theoretical values

P_v : Buckling load (Formula Karlsruhe)
P_{krx} : Flexural buckling load
$P_{kry,T}$: Torsional flexural buckling load

Theoretical exact values

Torsional flexural buckling loads
— Test results
━━ Calculated buckling load (Formula Karlsruhe)
─·─ Calculated flexural buckling load
─ ─ Calculated torsional flexural buckling load

(German Standard DIN 4114)

Fig. 8 — Comparison of test results with buckling loads due to Formula Karlsruhe and German Standard DIN 4114

199

horizontally supported or) for braced frames; for unbraced frames, and this holds not only for the "Elastic-Design"but also for the "Plastic-Design" (th.i. german "Traglast-Verfahren"), only the "Nonlinear-Theory" can deliver accurate results. In this connection we maintain that the equilibrium must be considered for the displaced system, not only in the simplified plastic configuration but also in the elastic situation.

Figure 6 shows:

1. The collapse results by way of "torsional flexural buckling"!

2. The deformation curves by flexure and also by torsion, indicate clearly the ultimate load - and not the bifurcation load; but all deformations start directly from initial-values (= geometrical imperfections).

3. The limit-loads can be found to a very good approximation by the formulae (fig. 3); on the other hand roughly estimated values for the "allowable strength" (as in the German standard DIN 4114) are not sufficiently accurate. By the tests No. 1 and No. 2 it was shown that (instead of $vK = 2,5$) the security-factors were only 1.49 and 1.16 respectively; test No. 3 would have been only 0,84, but here simple stress-calculation $N/F \pm M/W < zul\, \sigma$ gives protection - but not clearness.

The next series of tests had to clear up the usefulness of the formulae (fig. 3), if the load is piled up within the small area of section between the center of gravity and the shear-center.

The "Classical-Theory" gives us, for this interesting special sphere, the curves of fig. 7; depending on the different effective buckling lenght in the x- or y-direction, and as a function of the load-point. For practical designing each of the lowest side-branches of these curves should be taken as basis.

The formulae (fig. 3) revale and demonstrate a good and safe adaption, although related to the center of gravity of the cross-section. What's more, the "Classical-Theory" would not be applicable in the elastic-plastic-range.

Left in fig. 8 experimental values can be offered; in this figure, by the way, it is the arithmetical values according to the German-Standard-DIN 4114, which are shown, Not only left but also right one can recognize the weakness of the standardized procedure; on the other hand the formulae of

<u>fig. 3</u> describe the reality in a satisfactory manner (Probably, on the left side the ultimate loads would have been some what higher, if as a result of entering the elastic-plastic range, buckling of the flanges had not occured (<u>fig. 9</u>).)
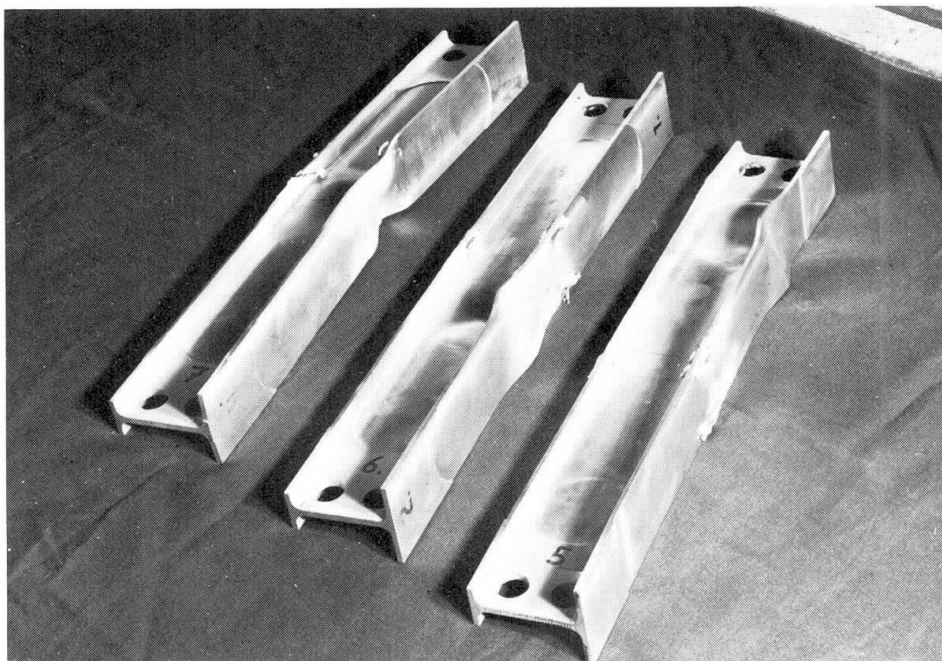

Fig. 9 Specimens after Testing

<u>Summary</u>

In regard to the instability of (single) <u>members</u> in a aluminium-structure (i.e. of columns) - and also of members <u>in frames</u>, loaded in a manner which does <u>not</u> produce transverse displacements at the floor levels -, it seems possible to propose a calculating method (see fig. 3) which covers "overall buckling with excessive bending" as well as the "lateral torsional flexural buckling"; this is valid so far as the cross section of the strut has a I-form and is loaded within the web-plane.

For practise design it seems alternatively possible to use tabulated "ω-values" (for planned-centrical loading) and, as a rough estimate, the "0.9 formula" (DIN 4114) for excentrical loading. -

In both cases knowledge primarily of P_{cr} (that is the bi-furcation-load, which is always greater than the stability-limit-load P_S) is an important tool for assessing the strength, also of (braced) systems (see lit. Andelfinger, Der Stahlbau 1964). -

At last the problem of frame-buckling (= general system buckling) with lateral free joints is to be discussed. Here in every case an (elastic) secondary order analysis seems useful (1. Klöppel-Friemann, Der Stahlbau, 1964; 2. H.Rubin, Dissertation, University Karlsruhe, 1971; 3. P. Dubas T.C. 17, Planning and Design of Tall Buildings, S.O.A. Report Nr. 5, 1972). If there are not lateral loads, then initial dis-placements for the joint levels should be assumed.

In as far as the mentioned (lateral free) frames are only one or two storeys high numerous tabulated values are available for the ideal effective length (S_{ki}); in this connection, the generally known "0.9-formula" (DIN 4114) is indeed being applied, but as regards this important sphere of application investigations are being conducted covering a more realistic and accurate use of the formulae of figure 3.-