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Stainless Steel Structural Members: Strength and Behavior

Eléments de construction en acier inoxydable: résistance et comportement

Konstruktionen aus rostfreiem Stahl: Festigkeit und Verhalten

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Structural Applications

Stainless steel is gaining increased use in building construction. Applications of this material are found when one or more of its desirable characteristics render it appropriate — resistance to corrosion, easy maintenance, attractive appearance, and, in the harder grades, a favorable weight strength ratio.

The relatively high cost of stainless steel — up to four more times that of ordinary carbon steel — in general restricts its economical structural use to cold-formed, thin-walled members or composite facings. Typical applications [1, 3] include curtain wall panels, mullions, door and window framing, roofing and siding, fascia, gutters, railing, stairs, street lamp poles and other tubular members, railroad passenger and specialty cars, tanks and other installations for the chemical industry, and a variety of special uses. Fig. 1 shows a few of the wide range of shapes which have been utilized in the past.

Thicknesses common in building construction range from 0.013 in. to 0.375 in. (0.33 to 9.52 mm) for formed sections. The approximate maximum width thickness ratio of stiffened elements (supported along both unloaded edges) is 200 to 250; of unstiffened elements (supported on one unloaded edge and free on the other) about 50. The maximum diameter thickness ratio of cylindrical tubular members is over 600. Load carrying members probably do not reach these high ratios, but may reasonably reach 150 for stiffened elements, 30 for unstiffened elements, and 100 for cylindrical tubular members. In addition, considerable use is made of curved elements other than cylindrical tubes.

A few particular types of stainless steel are important in structural applications; these types constitute the largest portion of stainless steel produced in the United States today. They are, using the American Iron and Steel Institute numbering system: 201, 202, 301, 302, 304, 316, and 430. All are austenitic except Type 430, which is ferritic.

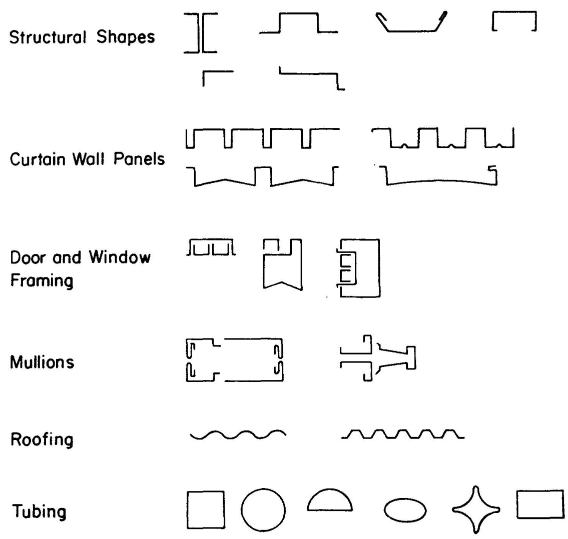

Fig. 1. Typical stainless steel sections.

Properties of Stainless Steels

Stainless steel is manufactured in a large variety of types to meet differing service requirements. There are three major groups of stainless steels — chromium, hardenable by heat treatment (martensitic); chromium, nonhardenable by heat treatment (ferritic); chromium-nickel and chromium-nickel-manganese, nonhardenable by heat treatment (austentiic). The ferritic and austenitic groups are hardenable only by cold working. The austenitic group in particular may be cold worked to a wide range of mechanical properties.

Chemical Composition

Stainless steels gain their corrosion resistance from the chromium content. A 12 percent chromium content renders the metal passive in those environments which do not continually break down the inert film of chronic oxide which is formed over the entire surface of the metal in a normal oxidizing atmosphere [2].

The chemical ranges of the stainless steels of particular interest in structural applications are shown in Table 1. Variations within or modifications to these groups are made for particular purposes, such as improving weldability, operating in varying corrosive environments, etc.

Table 1. Percent chemical ranges of selected stainless steels
(from AISI steel products manual [3])

AISI Type	C max.	Mn max.	P max.	S max.	Si max.	Cr	Ni	Other
201	0.15	5.50/7.50	0.060	0.030	1.00	16.00/18.00	3.50/5.50	N 0.25 max.
202	0.15	7.50/10.00	0.060	0.030	1.00	17.00/19.00	4.00/6.00	N 0.25 max.
301	0.15	2.00	0.045	0.030	1.00	16.00/18.00	6.00/8.00	
302	0.15	2.00	0.045	0.030	1.00	17.00/19.00	8.00/10.00	
304	0.08	2.00	0.045	0.030	1.00	18.00/20.00	8.00/12.00	
316	0.08	2.00	0.045	0.030	1.00	16.00/18.00	10.00/14.00	Mo 2.00/3.00
430	0.12	1.00	0.040	0.030	1.00	14.00/18.00		

Stainless steels can be welded by most methods; however, greater care is necessary in observing heat controls and duration of welding time. Of particular concern is the fact that under certain conditions sensitization may occur, that is, a region adjacent to the weld may become deficient in chromium, and therefore susceptible to corrosive attack. Another difficulty may arise in a local annealing effect, which will result in a locally lower strength.

Mechanical Properties

The stainless steels of primary use in structural applications have mechanical properties which differ considerably from those of ordinary carbon steel sheet and which make the existing codified methods [4] of design for carbon steel sheet inapplicable to stainless steel sheet.

There are four major differences: 1. the strong effects of cold working in increasing strength, 2. anisotropy, which increases with increasing amounts of cold working, 3. different shapes of the stress strain curves in tension and compression, and 4. a low proportional limit, particularly in compression.

Typical stress strain curves — tension and compression, longitudinal (parallel to the rolling direction) and transverse (perpendicular to the rolling direction), all in the plane of the sheet — are shown in Fig. 2 for Types 301, 302, and 304 stainless steel. The lowest set of curves is for annealed and skin passed (a one to three percent reduction by cold-rolling, made to improve flatness and surface appearance) sheet, Rockwell B 82 hardness.

The marked difference between longitudinal compression and the other three curves indicates that the common tension test is insufficient for prediction of structural behavior in compression. In particular, for any question of stability, performance would be grossly overestimated if the tensile properties are used.

The higher sets of curves are for half hard and full hard sheets. These hardnesses are achieved by cold reduction of the flat sheet, and correspond, roughly, to Rockwell C 32 and C 41, respectively. It can be seen for both hardnesses that the transverse compression curve is highest, the longitudinal

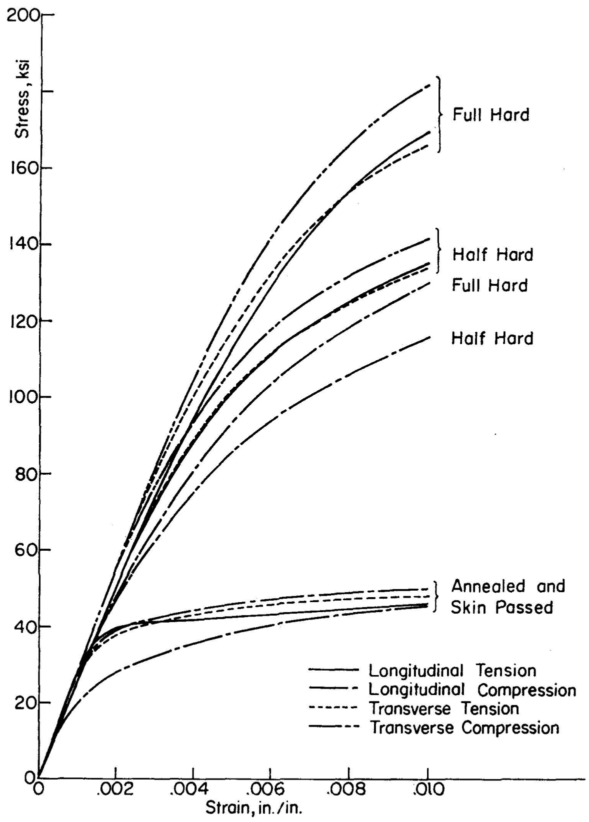

Fig. 2. Typical stress vs strain, types 301-302-304 stainless steel (from WATTER and LINCOLN [5] and authors' tests).

and transverse tension curves are slightly lower, while the longitudinal compression curve is considerably lower. Accompanying the increase in the strength by cold working is a slight decrease in the initial modulus of elasticity, which ranges from 26,600 to 29,600 ksi (18,702 to 20,811 kg/mm^2) for the annealed sheet.

The low proportional limit for all hardnesses is apparent in Fig. 2. Although accurate determinations have not been made, it is evident that the proportional limit may be as low as one-sixth of the 0.2% offset yield stress in longitudinal compression, but somewhat higher for the other three curves.

Representative mechanical properties of Types 301, 302, and 304 are listed in Table 2. The increase of the ultimate tensile strength by cold-rolling is accompanied by a reduction of ductility as indicated by percent elongation. The directionality induced by cold working is represented by the increase in variation of 0.2% offset yield stresses with increase in hardness. Also, the spread between tensile yield and ultimate strength decreases from approximately 150% in the annealed condition to as low as 23% in the full hard temper.

Cold formed corners are also strengthened by cold working. Fig. 3, for annealed and skin passed Type 304 stainless, indicates the stress strain curves for longitudinal tension and compression for both flat and corner material.

Table 2. Typical mechanical properties of types 301, 302 and 304 stainless steels

Temper	Annealed	¼ hard	½ hard	¾ hard	Full hard
Ultimate tensile strength	92 ksi (64.7 kg/mm²)	125 (87.9)	150 (105.5)	175 (123.0)	185 (130.1)
% Elongation in 2 in. (5.08 cm)	40	25	18	12	9
Yield stress (0.2% offset):					
Longitudinal tension	38 ksi (26.7 kg/mm²)	78 (54.8)	113 (79.4)	140 (98.4)	150 (105.5)
Longitudinal compression	34 (23.9)	67 (47.1)	85 (60.0)	95 (66.8)	99 (69.6)
Transverse tension	36 (25.3)	77 (54.1)	111 (78.0)	135 (94.9)	144 (101.2)
Transverse compression	38 (26.7)	80 (56.2)	119 (83.7)	150 (105.5)	160 (112.5)
Initial modulus	26,600 to 29,600 ksi (18,702 to 20,811 kg/mm²)				
Poisson's ratio	0.28 to 0.30, annealed				

(Note: Compiled from authors' test results and WATTER and LINCOLN [5]).

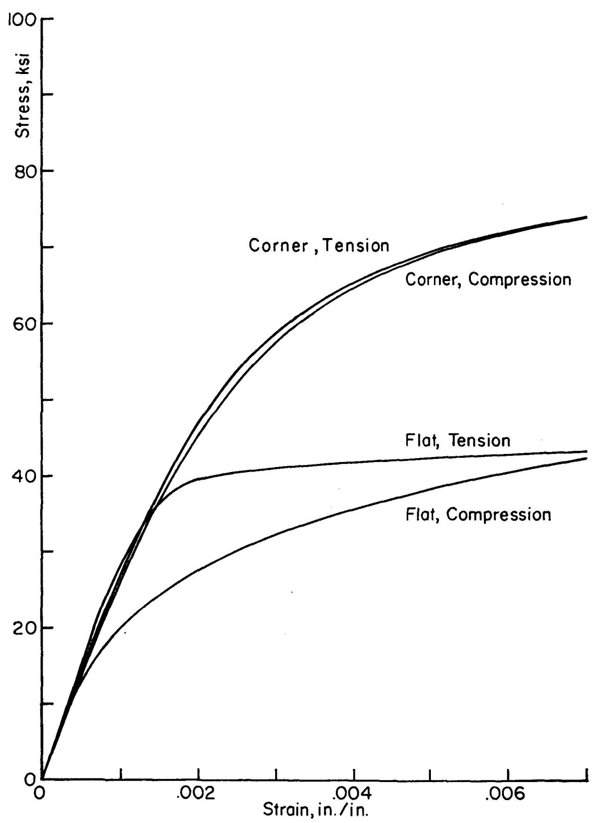

Fig. 3. Stress vs strain, flats and corners, longitudinal, type 304 stainless steel, annealed and skin passed.

The corners had a radius to thickness ratio of two (formed on a hydraulic press brake without bottoming the die). It is apparent that a formed section with a large percentage of corner material will be significantly stronger than the flat sheet properties would indicate. This difference is largest for annealed material and decreases with increasing hardness of the flat sheet, becoming almost negligible for the full hard grades.

Stainless steel can be formed by most conventional coldforming methods [6]. More energy is required than for forming carbon steels, and heavier equipment is needed. Greater attention must be paid to springback, and, particularly in the harder grades which have less ductility, care must be taken to avoid cracking. Because of the capacity of stainless for work hardening, the final forming resistance is high, especially for the annealed grade. An attempt is therefore usually made to complete the forming process in one continuous operation. Low forming speeds should be used, since stainless is sensitive to rate of deformation.

Structural Performance

In light gage construction, because of the large width thickness ratios which may be encountered, local buckling and post buckling behavior is of major importance. This problem will be briefly discussed below, as well as essential aspects of flexural behavior and column action.

Local Buckling and Post Buckling Behavior

The stress which initiates buckling of sheet and plate has been well established. Of particular interest is behavior after buckling, that is, what strength is available after the sheet has buckled. This strength has been successfully treated in the case of other materials and carbon steels in particular [7, 8] by the concept of effective width. This concept, originated by VON KÁRMÁN [9], replaces the non-uniform stress distribution over the full width w after buckling by an equivalent uniform stress distribution, equal in intensity to the edge stress σ_{max} but applied over an effective width b. Fig. 4 illustrates this idea for a compressed element stiffened along both longi-

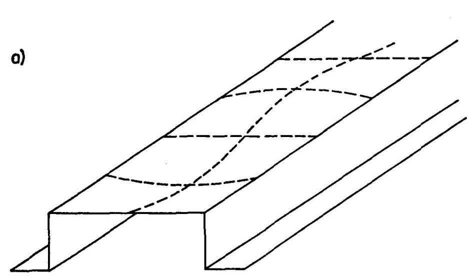

Fig. 4a)

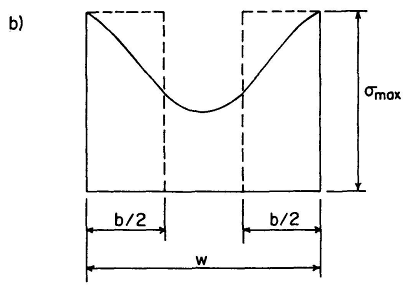

Fig. 4b)

tudinal edges. The research on carbon steel [7, 8] resulted in the following experimental modification of VON KÁRMÁN's relation

$$\frac{b}{t} = 1.9\sqrt{\frac{E_0}{\sigma_{max}}}\left[1 - 0.475\frac{t}{w}\sqrt{\frac{E_0}{\sigma_{max}}}\right], \tag{1}$$

when

$$\frac{w}{t} \geqq 0.95\sqrt{\frac{E_0}{\sigma_{max}}}. \tag{2}$$

For values of w/t smaller than given by Eq. (2), $b = w$.

Here b = effective width of compression element stiffened on both unloaded edges (see Fig. 4),
t = thickness,
E_0 = initial modulus of elasticity,
σ_{max} = compression element edge stress (see Fig. 4),
w = flat width of the compression element (see Fig. 4).

Eq. (1) can be non-dimensionalized to the straight line

$$\frac{b}{t}\sqrt{\frac{\sigma_{max}}{E_0}} = 1.9 - 0.9025\frac{t}{w}\sqrt{\frac{E_0}{\sigma_{max}}}. \tag{3}$$

In order to determine effective width relation for a stiffened element of annealed Type 304 stainless steel a series of tests of shallow hat section beams was made. The center half of these beams was under a uniform moment so that the compression flange behaved as a compression element stiffened along both unloaded edges by the webs. Details of the test procedure and results have been presented elsewhere [10]. Fig. 5 reproduces these results, where the straight line determined for carbon steel is also shown. It can be seen that a remarkably close agreement exists between the experimental results for annealed

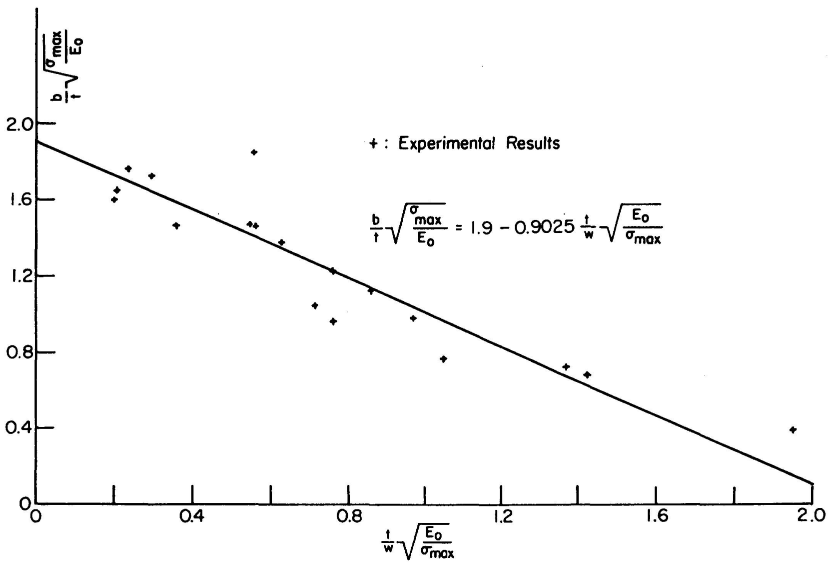

Fig. 5. Experimental effective widths, type 304 stainless, annealed and skin passed.

Type 304 stainless and the empirical relation for carbon steel. This fact is somewhat surprising because of the different stress-strain curve for stainless as compared to carbon steel. The explanation is that for carbon steel Eq. (1) represents a conservative expression which lies close to the lower limit of experimental scatter. For stainless steel the same expression is seen to define quite closely the center of the scatter band (see Fig. 5). Actually, therefore, for a given w/t-ratio the postbuckling strength of stainless steel on the average is somewhat lower than for carbon steel.

An investigation now in progress on elements stiffened only along one longitudinal edge indicates, likewise, that post buckling strength can be represented by a relation similar to Eq. (1) except that the constants are different. Again, this was also found to be the case for ordinary carbon steel unstiffened elements [7].

Associated with stresses in the post buckling range are out of plane distortions. These distortions are small and disappear upon removal of the load, provided the proportional limit is not significantly exceeded. Since the proportional limit for stainless steels is considerably lower than that of carbon steels, it is obvious that less of the post buckling strength can be utilized in stainless members if good appearance is important.

Flexural Strength, Deflections

In calculating the flexural capacity of stainless steel beams it is necessary to resort to the basic equations of beam statics

$$\int_A \sigma \, dA = 0 \tag{4}$$

and

$$\int_A y \, \sigma \, dA = M, \tag{5}$$

where
σ = stress,
A = area,
y = distance from neutral axis,
M = bending moment.

Because of the low proportional limit, linear relations are not applicable and one must use numerical calculations based on the actual stress strain relations to evaluate Eqs. (4) and (5). Thus, Eq. (4) locates the neutral axis, and Eq. (5) defines the bending moment.

Similarly, deflections cannot be calculated by the customary elastic relations. Recourse must be had to the relations between bending moment, extreme fiber strains and curvature, again calculated numerically based on the actual stress-strain curve.

Procedures and results for a series of stainless steel beams have been reported previously [10]. Good agreement was found between calculated and experimentally measured strengths and deflections.

Column Strength

It is generally accepted that column strength in the inelastic range can be calculated by Engesser-Shanley's modification of the Euler formula

$$\sigma_{cr} = \frac{P_{cr}}{A} = \frac{\pi^2 E_t}{(l/r)^2}, \tag{6}$$

where
σ_{cr} = critical column stress,
P_{cr} = critical column load,
A = area,
E_t = tangent modulus corresponding to σ_{cr},
l = effective length of column,
r = radius of gyration about buckling axis.

A brief series of tests [10] has verified this relation for annealed Type 304 stainless steel. Basing the column curve on the compressive stress strain curve of the flat material only (Fig. 3) resulted in deviations of experimental from calculated strength values up to 18%, the experimental values being higher. When the increased strength of the corner material was taken into account in determining the effective tangent modulus E_t, the strength of compression member could be predicted from Eq. (6) with an error not exceeding $\pm 4\%$. The calculated column curve, where the increased strength of the corners was taken into account, and experimentally measured values are shown in Fig. 6.

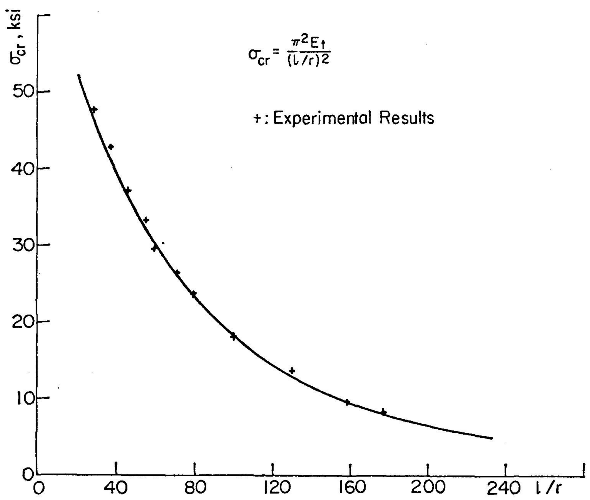

Fig. 6. Column curve, type 304 stainless Steel, annealed and skin passed.

Acknowledgment

Much of this paper is based on the initial results of an extensive and continuing investigation of the performance of stainless steel structures sponsored at Cornell University, Ithaca, N.Y., by the American Iron and Steel Institute, New York, N.Y.

List of Notations

A	area
b	effective width of compression element
E_0	initial modulus of elasticity
E_t	tangent modulus
e	effective length of column
M	bending moment
P_{cr}	critical column load
r	radius of gyration
t	thickness
w	flat width of compression element
y	distance from neutral axis
σ	stress
σ_{cr}	critical column stress
σ_{max}	compression element edge stress

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Summary

The importance of stainless steel as a structural material is increasing rapidly. A considerable variety of such steels can be used by the designer for his specific situations. The structural performance of stainless steel members is strongly influenced by the peculiar mechanical behavior of this material: its low proportional limit, the unusual shape of its stress-strain curve, its pronounced anisotropy, and the strong effects of the strain hardening which occurs in cold-forming structural shapes from flat sheet. Although the usual concepts and methods of structural design and analysis apply to stainless steel, they must be modified in many respects, to reflect the described peculiarities of the material. This is illustrated by brief discussions and test results in regard to the post-buckling strength of thin compression plates, the behavior of flexural members, and the buckling strength of columns.

Résumé

En tant que matériau de construction, l'acier inoxydable prend une importance qui ne cesse de s'accroître rapidement. Il en existe une variété très étendue qui s'offre à l'ingénieur pour chaque cas particulier. Dans les ouvrages, le comportement des éléments en acier inoxydable est étroitement lié aux propriétés mécaniques de ce matériau: sa limite de proportionalité est basse, sa courbe contraintes-déformations a une forme inhabituelle, son anisotropie est accusée, et l'écrouissage qui se manifeste dans les profilés travaillés à froid à partir de feuilles de tôle a des effets très sensibles. Bien que les principes et méthodes classiques de l'étude et du calcul des ouvrages s'appliquent à l'acier inoxydable, il faut toutefois les modifier à maints égards pour prendre en compte les particularités inhérentes à ce matériau auxquelles il vient d'être fait allusion. Ces considérations font l'objet d'une brève discussion complétée par la communication de résultats d'essais concernant la résistance post-critique des plaques minces comprimées, le comportement des éléments travaillant à la flexion et la résistance des barres comprimées au flambement.

Zusammenfassung

Die Anwendung von rostfreiem Stahl für konstruktive Zwecke ist in schneller Zunahme begriffen. Eine beträchtliche Auswahl von verschiedenen Stählen steht zur Verfügung zur Anpassung an besondere Forderungen. Unter Belastung ist das Verhalten von Baugliedern aus rostfreiem Stahl sehr stark von den Besonderheiten der Materialeigenschaften beeinflußt: von der niedrigen Elastizitätsgrenze, von der ungewöhnlichen Form der Spannungs-Dehnungs-

Kurve, von der stark ausgebildeten Anisotropie und von den beträchtlichen Folgen der Kaltverformung, die bei der Herstellung von Profilkörpern aus flachem Blech oder Band eintritt. Wenngleich die Begriffe und Methoden der Baustatik und Festigkeitslehre auch für den rostfreien Stahl gelten, so müssen sie doch in mancher Hinsicht den Eigenheiten dieses Materials angepaßt werden. Als Beispiele dafür werden in Kürze und mit Versuchsergebnissen das postkritische Verhalten ausgebeulter dünner Platten, die Besonderheiten der Biegungsverformung und -festigkeit und das Knicken von Druckgliedern behandelt.