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Master's diploma at the Faculty of Civil Engineering of Warsaw University of Technology, in the field of construction, on the specialization of building and engineering constructions, with the title of Master of Science in civil engineering.
Diploma number: 4186/111025, dated November 3, 1983.

Diploma of a PhD degree in technical sciences, in the field of robotics and automation, issued by the Institute of Fundamental Technological Research PAS, in Warsaw, on March 19, 1992, on the basis of the presented dissertation titled "Stability of discrete-continuous systems subjected to non-conservative loads" .

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Warsaw University of Technology,

Faculty of Building Installations, Hydrotechnics and Environmental Engineering,
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01.2008 - 30/09/2010 - Laboratory of Control and Dynamics of Systems in the Division of Intelligent Technology

07.1990-12.2007 - Independent Laboratory of Dynamics and Stability of Machines and Vehicles

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10.1997 - 09.2008 Institute of Water Supply and Hydro-Engineering of the Faculty Environmental Engineering

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4. Depicted achievements resulting from art. 16 sec. 2 of the act of 14 March 2003 on academic degrees and academic title and on degrees and title in the field of art (Journal of Laws no. 65, item 595, with amendings):

Szymon Imiełowski, "**Deformation, elastic strain energy in stability analysis of engineering structures**", in the publishing series "Studies in Engineering", published by the Committee of Civil and Water Engineering of the Polish Academy of Sciences, No. 102, 193 p., Warsaw 2019

Reviewers: prof. dr hab. Wacław Szcześniak, prof. dr hab. Jacek Przybylski

Description of the scientific purpose of the above work and achieved results together with a discussion of their possible application.

Description of buckling and stability loss of prismatic bars, of typical rolled cross-sections, used in the construction industry, in a wide range of slenderness, is considered in this book. Thin-walled profiles and questions of local loss of stability are not taken into account.

A structural system is defined as a structure together with a load and examples of elastic constructions are considered. In this case the energy balans is determined by the type of loading. The generalized follower force is taken as loading, that allows extended analysis of the energy models of the system. Examples of conservative and non-conservative systems in which energy is added to the system are taken into account. The model of the generalized force in which the current force position, determined by the eccentricity *e* of the force application point with respect to the section centroid and the angle χ , that the force vector create with the tangent to the bar axis, are changing during loading process. They are considered as the linear function of lateral displacement and the angle of rotation of the cross-section at which the force is applied, described by four parameters: $\bar{\rho}, \bar{\vartheta}, \bar{\mu}, \bar{\gamma}$. Selected cases of a generalized force are the force of a constant direction and point at cross-section (Euler's problem) and force tangent to the axis of the bar (Beck's problem). A taken into account, wide range of loads made it possible to distinguish construction features that determine its loss of stability.

Scientific goal of the presented work

a) The primary purpose of the research was to verify current models of the phenomenon of stability loss in terms of all the effects that are observed in the experiment. Modern research results indicate that explanation of the bars buckling and stability loss, based on the bifurcation of the equilibrium position does not fully correspond to the observed bar behavior at conditions of critical state. The deflection of the bar axis appears in the sub-critical range. In the literature one distinguishes the concept of a mathematical model of buckling, from the buckling observed in the experiment. The presence of imperfection is actually considered as a main reason of the deflection of the bar curvature at critical state. Such approach causes that the description of buckling is usually associated with a specific class of cross-section and material from which the construction element is made. Currently, there are no unified methods for calculating buckling structures. There is still a wide variety of national standard recommendations.

b) A reliable description of the buckling and loss of stability phenomena is provided by the energy criterion, in which the level of elastic strain energy is considered as parameter determining the material effort. Moreover, the critical state is described by a condition of the maximum strain energy which can be accumulated in the compressed rod volume that results in loss of ability to elastic deformation. This approach differs from the known energy criterion, in which the total potential energy of the system is minimized. The proposed criterion of elastic strain energy has already been verified on the example of circular cross-section samples made of high-strength steel. Willingness to verify this criterion in the case of any material and any shape used in engineering practice, i.e. economic profiles: angles, channels or tees, and an explanation, whether the proposed definition applies to the loss of stability of non-conservative systems, was the motivation for undertaking of this research also. How the intensity of elastic energy is included in the analysis carried out with the use of the dynamic stability criterion?

c) Changes of stiffness strongly affects the compressed bar stability. Increasing of the load results in reducing of the lateral stiffness of the bar loaded by a force of constant direction. In this case the natural frequency ω, is considered as the transverse stiffness measure. One observes decreasing of this frequency during loading. In case when the energy is supplied to the system by load, e.g. the in case of liquids or gas flow, the response of system is completely different. In this case, increasing of loading causes stiffening of the structure and the increase of the basic eigenfrequency. Investigation of the changes of the system stiffness during loading process was another motivation of the undertaken research.

d) Another goal of this research was to describe the deformation of the bar during compression process. The Euler solution takes into account only deformation which describes the state of the bar under critical force, namely deformation of a curved incompressible bar. Euler solution gives results that describes well the stability loss of real slender bar. The question is, how to describe deformation from the beginning of the bar compression, so that it stays in line with the Euler model?

e) Analysis of the structural post-critical response was an additional motivation for this study. The importance of the question of possible post-critical strengthening arises from the point of view of structural robustness. The results of experimental research carried out, indicate that non-zero load-bearing capacity in the post-critical load range is possible. The open question relates to the structural performance conditions at which, a non-zero the post-critical bearing capacity is accepted.

f) In the case of a non-conservative or pseudo-conservative loadings, the stable behavior of the structure is determined not only by the actual intensity of the elastic strain energy, but also by the amount of energy added to the system by the follower type loading. The energy added to the system may cause amplification or suppression of eigenforms. Also, it can be a reason of a qualitative variation of the eigencurves shape, namely the change of actual shape into a shape that corresponds to a higher energy level. The value of the critical force corresponding to the higher eigenform is much higher than the critical force of the lower form. One of the motivations was to examine how the shape of the eigenform relates to the energy balance of the system and how the increased load capacity resulting from the loss of stability with a higher eigenform can be used in engineering practice.

g) In view of the fact that the critical state is determined by the level of elastic strain energy and not by the critical stress limit, a new definition of safety factors should be proposed, in which the concepts of elastic strain energy would be included. In current standards, safety coefficients usually refer to material strength characteristics.

h) In Euler approach the limit slenderness of the elastic buckling λ_H is defined by the straight shape of the bar. This is not a good approach for real column, where under conditions of the stability loss the axis of the bar is curved. A proposition of a new classification should take into account the curved shape of the bar under critical loadings. Creation of such classification was another motivation for undertaking of this research.

Answer the formulated above questions has required a series of theoretical studies and experimental tests. The main results were obtained as a result of the of NSC research projects conducted under my direction:

1. Habilitation research project, 1173/B/T02/2011/40, " Energy criterion in the analysis of stability and dynamics of engineering structures. Selected methods of structural safety assessment.", 13.06.2011-12.06.2012, National Science Centre
2. Research project N50104131/2765: *„Analysis of critical and post-critical states under conservative and non-conservative loads. Experimental and theoretical research, verification of existing design standards”,* 15.11.2006 - 30.12.2009, National Science Centre
3. Research project 7 T07A 00419 *„Analysis of dynamics and stability of non-conservative and pseudo-conservative mechanical systems. Theory and experimental verification.”*, 1.07.2000-31.03.2004, National Science Centre

A brief description of the monograph content

On the beginning of the presented monograph, the theoretical models of stability of columns subjected to conservative and non-conservative loads were treated. As example of conservative systems the Euler and Lagrange's problems were discussed in details. It was pointed out, that in both cases the solution of the problem is possible, when the condition of the maximum elastic strain energy is taken into account. Then the issues of elastic strain energy and stiffness in the stability approach, including the influence of this energy on the stability loss were discussed. It was shown how the condition of maximum strain energy is included in the description of selected criteria of the loss of stability. The classification of slenderness of compressed bars that took into account the condition of maximum elastic strain energy has been proposed. In case of static analysis the model of evolution of the bar deformation during compression is proposed and explained on the base of relation between total elastic strain energy and elastic shear energy. Three deformation stages have been distinguished: deformation of a rectilinear bar, intermediate stage in which the shear deformation and deflection of the bar axis appears and the third stage defined by deflection of the incompressible bar. In the case of analysis perfomed with the use of the dynamic criterion deformation modes were defined as a set of eigenforms corresponding to the given load, and the phenomenon of qualitative change in eigenforms was explained on example of non-conservative and pseudo-conservative systems. The method of stability analysis based on the observation of the changes of the characteristic curves shape is discussed.

The main portion of the monograph creates a description of the stability experiment of bars of cross-section and slenderness used in civil- and hydro-engineering practice. An original testing program was proposed, which was carried out in the laboratories of the Department of Strength of Materials at the Institute of Fundamental Technological Research of the Polish Academy of Sciences and the Department of Strength of Materials of the Faculty of Civil Engineering at the Warsaw University of Technology. The book includes description of the stability tests of aluminum and steel flat bars, rolled profiles and steel plate strips as well as the analysis of the obtained results. In the selected tests, the strain measurements of the bars side surface performed by strain-gauges were performed.

Discussion of the research results and the main elements of the proposed stability hypothesis

The buckling model, in which the elastic strain energy is consider as a parameter describing the effort of the bar material and in which the separation of the bar deformation stages are considered. This is a non-standard approach to the stability problem. One of the main results of the presented analysis is to show, that the existence of the bar lateral deflection is independent of the presence of material or geometrical imperfections. The results are discussed on example of conservative systems whereas some details relates to non-conservative ones.

a) It is emphasize, that a full description of the stability phenomenon is possible, when various methods of the stability experiment results are used.

The current value of the force P, the maximum bar lateral deflection f and the displacement u in the direction of the acting force, were recorded during experiment. The results were presented in the form of variation of the registered parameters in time, $P = P(t)$, $f = f(t)$, $u = u(t)$, as well as diagrams of $P = P(u)$, $P = P(f)$, $f = f(u)$, $u = u(f)$, $\varepsilon = \varepsilon(u)$, $\sigma = \sigma(u)$, where ε is a longitudinal strain, $\sigma -$ normal stress. Example diagrams are shown in Fig. 1 and 2. Each of the presented methods of reporting results brings a new element to the analysis. From the diagram $P = P(u)$, variation of displacement u can be determined at any stage of the compression process. This makes possible to determine the stiffness of the bar. The energy of the process can be calculated as the area under the curve. The jump phenomenon at stability loss in the range of middle slenderness is clearly visible, but the limits of the transient stage of deformation are not noticeable. The magnitude of the force P^*, at which the transverse displacement appears (the lower limit of transient stage), can be read from the $P = P(f)$ diagram, whereas the parameters of the upper limit of the this stage (u_z, f_z) are the coordinates of the graphs $u = u(f)$ and $f = f(u)$ inflexion point. Lateral displacement at critical or limit point can read from the $P = P(f)$ diagram also. The program of parameter changes in time: $P = P(t)$, $u = u(t)$, $f = f(t)$, supplements the description.

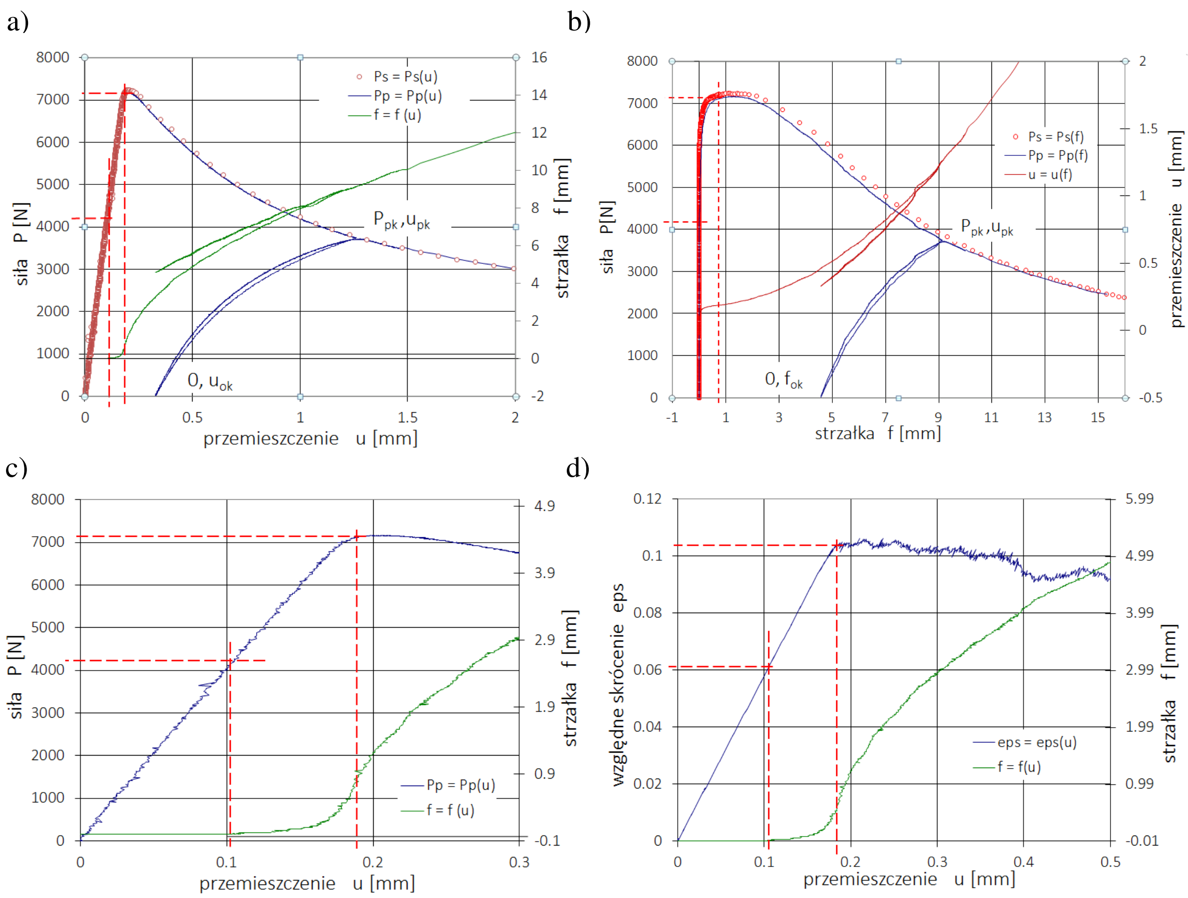

Fig.1. Diagrams of equilibrium paths, slender aluminium flat bar, $\lambda = 101{,}3$: a) and c) $P = P(u)$ and $f = f(u)$, b) $P = P(f)$ and $u = u(f)$, d) $eps = \varepsilon = \Delta l_{ef} / l_{ef}$ - relative shortening of the bar axis, P - loading, u – longitudinal displacement, f - max lateral displacement.
The dashed line indicates the beginning and end of the transient stage of deformation.

b) The new approach to the description of sub-critical deformations is proposed. In case of static analysis, three successively appearing stages of deformation have been distinguish, namely: shortening of the bar of rectilinear axis, transient stage (simultaneous eccentric compression and shear) and deflection of the bar of incompressible axis. The magnitudes of forces and displacements, defining the limits of deformation stages are determined. Mechanism of changing of deformation modes has been recognized and explained.

Finding the transient stage as a separate stage of sub-critical deformation is a new contribution to the stability of prismatic bars. The boundaries of the transient stage are marked in Fig. 1 and 2 with dashed lines. Formulation of the criterion of the upper limit of first deformation stage, in form of the maximum shear strain energy (Huber-Mieses-Henky criterion), appears the original result of this research also.

The limit is depicted by the force P^*, that is easily seen on the $P = P(f)$ diagram as point of the transverse displacement appearance. P^* can be determined from the formula $P^* = P_E / \sqrt{3}$, where P_E is the Euler critical force. For medium slenderness, P_E is the value of the Euler force that would be carried by a bar of a given slenderness and enough high limit of linear elasticity, which would ensures carrying the critical force in the range of linear elasticity.

At the transient stage shear deformation appears. The displacement of cross-sections, perpendicular to the bar axis, follows shear strain and displacement *e* of the point of the force application from the cross-section centroid appears. The bending moment, $M = Pe$, appears. Thus, the shear deformation appears simultaneously with the deflection and shortening of the bar axis. At the same time the intensity of normal strain does not change, the $P = P(u)$ and $\varepsilon = \varepsilon(u)$ graphs, Fig.1 c and d, show that the intensity of force and longitudinal strain increase does not change when switching to the transient stage. Increasing of the loading at transient stage results in increasing of bending and suppression of the longitudinal and shear deformations. On the end of this stage bending becomes the dominant load, and finally due to the small effect of shear and shortening of the axis, these deformations can be abandoned. The upper limit of the transient stage is determined by the point of inflexion on the diagrams $u = u(t)$ and $f = f(t)$, what is seen in Figs. 1 c and d.

The third stage of deformation is deflection of the incompressible bar.

The different reasons for changing modes during sub-critical range should be underlined. The reason for terminating the first stage lies in energy condition, namely achieving the maximum shear energy. The transition to the second stage is possible because the rectilinear shape is the common shape of the three types of deformation. A straight bar is a special case of shear deformation, in which the shear angle is equal to zero as well as it is a special case of the deflected bar with the angle of the cross-section rotation equal to zero. The condition for transition into the third stage of deformation is the stiffness condition. The transition to the deformation of the third stage occurs when the stiffness of curved bar in the direction of acting force is lower than the stiffness of the longitudinal strain.

c) An important achievement of this work is proposition of new classification of slenderness, which takes into account that under critical/limit conditions, the bar axis is curved.

The limit slenderness λ_k of bars that carry critical load, is determined by the stress at the most outer compressed fiber, equal to the limit of linear elasticity, i.e. limit of linear elasticity R_H or conventional limit $R_{0,01}$. The slenderness λ_k, is therefore bigger than the limit Euler slenderness λ_H, that is determined for straight shape. In the case of slender and large slenderness rods after moving to the third stage of deformation, the rods maintain a stable equilibrium position until the conditions of stability loss are reached.

The smaller slenderness, $\lambda_o < \lambda < \lambda_k$, are called medium slenderness, for which the loss of stability (limit state) is determined by the conditions of changing from the transient stage of deformation into the stage of the deflected incompressible bar. Such definition is a new interpretation of the limit state of stability loss.

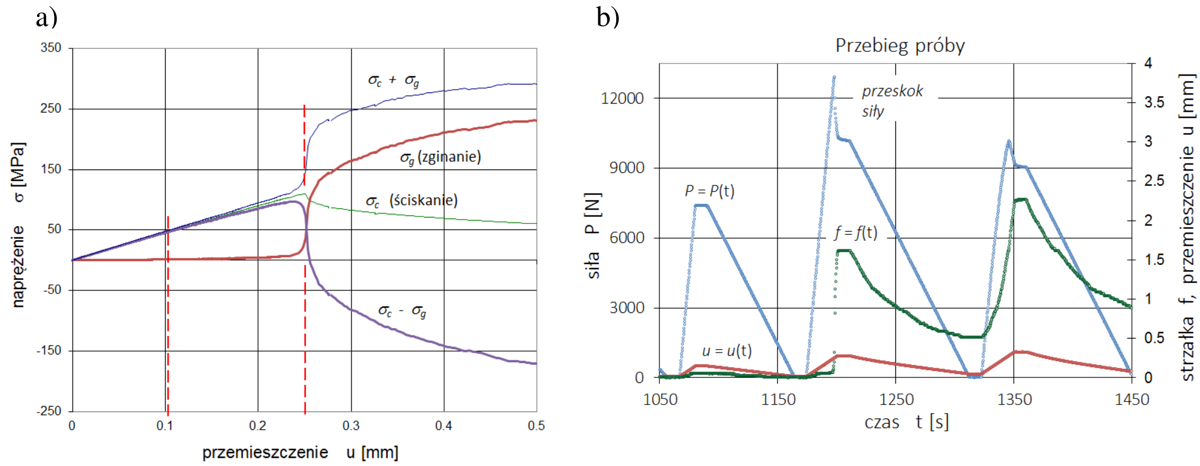

Fig.2. Diagrams of equilibrium paths, aluminium flat bar of medium slenderness $\lambda = 72{,}5$:
a) $\sigma = \sigma(u)$, b) $P = P(t)$, $u = u(t)$, $f = f(t)$, P - loading, u – longitudinal displacement,
f – max lateral displacement, $\sigma_c = P/A$ – compression stress, $\sigma_g = M/W$ – bending stress,
$M = P f$ – bending moment, A – cross-sectional area, W – section modulus.
The dashed line indicates the beginning and end of the transient stage of deformation.

In the range of medium slenderness, an interval was distinguished $\lambda_\Delta < \lambda < \lambda_k$, near the Eulerian slenderness λ_H , in which the loss of stability is associated with a jump decrease of loading $\Delta P < 0$, increase of lateral deflection $\Delta f > 0$ as well as increase of the stress $\Delta\sigma > 0$ in the outermost compressed fiber. Jumps are shown in Fig.2, where an example of aluminum bar of slenderness $\lambda = 72.5$ and conventional limit $R_{0.01} = 150$MPa is presented.

Jump phenomenon appears for medium slenderness, as an effect of instability of equilibrium position. It is associated with the change from transient stage into the stage of the deflected incompressible bar. Such interpretation is an original achievement of this work.

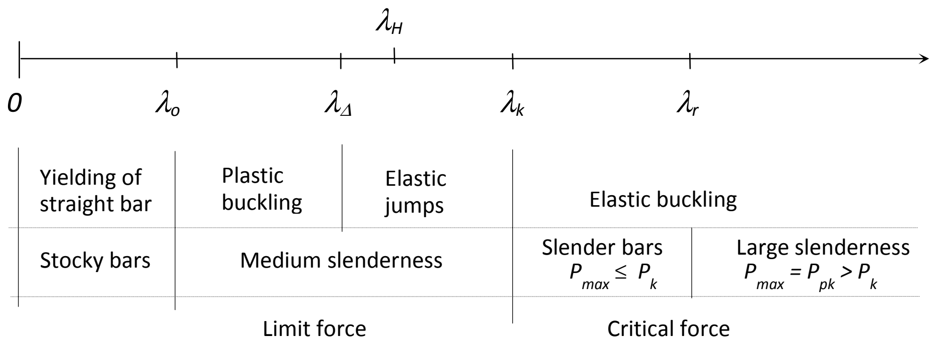

Fig.3. Classification of bars slenderness

The proposed classification of the slenderness of the compressed rods is as follows.

1. *The stocky bars* ($\lambda < \lambda_o$) compressed bar fails without buckling, maintaining the shape of a straight bar.

Medium slenderness range

2. *Plastic deformation interval* ($\lambda_o < \lambda < \lambda_\Delta$) - the limit state is determined by the limit force $P_n < P_k$, with plastic deformation of cross-sections.

3. *Elastic jump interval* ($\lambda_\Delta < \lambda < \lambda_k$) - the limit state is defined by the maximum force of jump $P_n = P_\Delta < P_k$, followed by the jump of force and deflection.

Bars carrying critical force

4. *Slender bars* ($\lambda_k < \lambda < \lambda_r$) - critical force P_k in the range of elastic deformation, post-critical force $P_{pk} \leq P_k$.

5. *Large slenderness* ($\lambda > \lambda_r$) - critical force P_k occurs in elastic range of deformation, an effect of post-critical increase of load capacity, $P_{pk} > P_k$, is observed.

where: λ_o - slenderness, below which buckling does not occur, λ_Δ - the lower slenderness limit of the elastic jump interval, λ_k - lower slenderness limit of bars that carry the critical force P_k, λ_r - lower slenderness limit of bars that carry post-critical force, $P_{pk} > P_k$.

d) In this study the definition of stable behavior of a slender structure, is defined as a state in which the system retains the ability to elastic deformation. This approach was verified.

e) In the study, the features of critical state that follow criterion of elastic strain energy were verified.

- Definition of a critical state at which the elastic strain energy takes the maximum value equal to U_H and the ability of bar to elastic deformations is lost, was confirmed.

- The relationship between the bending energy U_g, the compression energy U_{sc} and the maximum elastic strain energy U_H, given by the formula $U_H = U_{sc} + 2\,U_g$, was checked.

- The magnitude of the bar maximum lateral deflection at critical state was determined.

f) A new element proposed in this work, that relates to sub-critical deformation, next to separation of the transient deformation stage, is the conclusion that the critical shortening ε_k is the sum of both longitudinal deformations, the straight axis strain and transition stage strain. On the $P = P(u)$, $\varepsilon = \varepsilon(u)$, graphs, Fig.1 c and d, passing to the transient stage do not change the inclination of the graph curve tangent. This conclusion creates also a confirmation of the assumption on incompressibility of the bar at the third deformation stage.

Calculations of the critical strain ε_k were made throughout the entire range of slenderness covered by the test program. The results of the calculations indicate that the formula $\varepsilon_k = \pi^2 / \lambda^2$ is valid in the case of members that carry the critical force, for which the transition to the stage of deflected incompressible bar occurs in the range of elastic deformation.

g) The performed tests has confirmed that in case of the load applied by displacement increments, non-zero post-critical bearing capacity appears in bars that carry critical load. An effect of material strengthening follow the post-critical plastic deformation, in entire bar volume, that appears after achieving the maximum elastic strain energy at critical state. In the performed experiment, the strengthening was observed in a form of keeping a value of loading close to the critical one, along a wide range of displacement. The length of this displacement interval is direct proportional to the slenderness. The feature post-critical strengthening becomes important from a point of view of structural robustness.

Interpretation of the post-critical strengthening effect as a result of plastic deformation that appears in the entire bar volume after reaching the maximum elastic strain energy (losing of ability to elastic deformation), is a new element in the study of this phenomenon.

The paper indicates that in the post-critical range, the shape of the equilibrium path does not depend on the way of loading. It is the same in the case of static loading by increments of displacement as well as dynamic failure of the rod, which has lost its capacity due to applied loading that exceeds the maximum value. The uncontrolled process of the sample failure, during return of the testing machine head to resting position, was registered by displacement sensors. Indications of the sensors are marked with circles in Fig. 1b. The recorded load values show that the failed sample has a non-zero bearing capacity in the post-critical range.

h) Tests of unloading/reloading cycles, for all tested slenderness, revealed a *return point memory* feature. After unloading and reloading the bar returns to the point of the post-critical path from which the unloading has started. Points of coordinates (P_{pk}, u_{pk}) are marked in Fig. 1a and b.

i) Verification of some key elements of the proposed theory was possible due to strain-gauge measurements, of the bars lateral surface deformation $\varepsilon = \varepsilon(t)$. Particularly, this results:

- confirmed the correctness of the assumption of incompressibility of the bar axis in the third stage of deformation,

- confirmed the correctness of the assumption, of a simply supported bar as a static scheme for analysis; the strains at the bar inflexion point, nodes of the curved bar shape, appears to be equal zero,

- allowed a visualization of the phenomenon of force and deflection jump, at limit state of medium slenderness bars.

j) Variation of the bar stiffness were determined during compression process.

The stiffness of the compression bar should be defined for the current type of deformation. The Young's modulus is a measure of stiffness of a straight bar. Young's modulus is still a measure of stiffness during transition stage. That feature results from the dominant longitudinal strain. In the final part of this stage, the increasing influence of bending reduces the longitudinal stiffness. The slope of the tangent to the $P = P(u)$ diagram decreases. Finally the concept of the stiffness in the direction of compressive force should be used to analyse the stiffness of a curved rod of incompressible axis.

Increasing of the load of a bar subject to conservative force reveals in reducing of the bar lateral stiffness, whereas in the direction of acting force the rod remains stiff. Stability loss appears when the transverse stiffness takes zero value. The measure of the bar transverse stiffness is the natural frequency ω. It was noticed that an effect of decreasing of eigenfrequencies caused by increasing load is accompanied with suppression of the higher eigenforms and transferring the energy of the higher forms to the first one.

k) The influence of strain energy variation on the process of buckling and stability loss was defined.

In the case of conservative loading, the effect of decreasing of the frequency of vibrations is associated with suppressing the higher eigenforms and transferring the energy of the higher forms to the first one. Finally, the loss of stability takes place at the first eigenform only with frequency equal to zero. That corresponds to the monotonous, infinitely slow increase of the lateral deflection of the first eigenform. The structure loss its stability by divergence.

In the case of non-conservative or pseudo-conservative loading, the response of the structure is determined not only by the value of the elastic strain energy, but also by the energy added to the system through follower type loading. The energy added to the system increases its stiffness and the first eigenfrequency increases. This additional energy portion can cause an increasing of the eigenforms or it suppression. Also it can cause a qualitative change of the eigenform shape. Due to such changes the shape of the form corresponding to a higher energy level appears. The value of the critical force corresponding to the higher eigenform is much higher than the critical force that occurs with the lower form.

In the case of non-conservative system, a constant inflow of energy causes that the shape of the first eigenform approaches the shape of the second eigenform. The loss of stability by flutter takes place when the shape of the first two eigenforms is identical.

In the case of the pseudo-conservative system, the energy is supplied to the system in the initial stage of loading. It causes the increase of internal energy and the transition of the fundamental eigenfom to the shape of higher one. However at a certain level of load, boundary or load conditions stop the energy inflow and cause the change of the system response into the typical for the conservative one. Finally the structure loss stability by divergence, with the monotonic increase of the lateral deflection of the second form. Loss of stability with a higher eigenform appears with higher critical force. The phenomenon of changing of eigenforms was discussed in detailes on examples of the non-conservative Beck's column and the pseudo-conservative Tomski's column.

The explanation of the phenomenon of eigenform change from the point of view of energy supply resulting from the follower type of loading is an original achievement of this work.

The change from the first eigenform into the higher one it is preceded by suppression of the higher eigenforms, the only active form remains the fundamental one. At the load of P^*, the natural frequency ω^* of a bar loaded by generalized force is the same as the second natural frequency of the Euler bar, the structure exhibits features of the conservative one. The parameters of the point of eigenform change (P^*, ω^*) create a feature of the structure. They are the same for bars subjected to non-conservation, pseudo-conservation and conservative loads. This observation is a very important development of the proposed theory.

Suggestions for the possible application of the proposed solutions for improving the structural safety at conditions of stability loss.

a) The original concept of safety factor formulated in terms of energy

As the critical state is determined by intensity of elastic energy, and not by the level of stress, a definition of safety factor, based on the concept of elastic strain energy is proposed in the book. The condition of the safe structure performance was formulated in terms of energy. A definition of safety factor as the quotient of the elastic energy accumulated in the bar, U_S, to the maximum elastic strain energy U_H, $n = U_S / U_H$, was proposed. The maximum value of the elastic strain energy that can be accumulated in the bar volume depends on the geometric characteristics of the cross-section as well as strength and mechanical properties of the material, and is given by the formula $U_H = \frac{1}{2}\pi A i\sqrt{R_H^3/E}$, where: R_H is proportionality limit, E - Young's modulus, i - radius of inertia, A - area of the bar cross-section. The proposed formulation of the safety factor determines what part of the maximum energy U_H should be included in the design to ensure safe operation of the structure.

Loss of stability relates to the whole volume of the structure, not only to the most strained cross-section, it is a global phenomenon. Definition of the critical state in the form of maximum elastic strain energy U_H, approximate well this behavior. At critical point, due to loss of ability of elastic deformation, plastic deformation can appear, even in cross-section where stress level is less than the yield limit. The energy criterion formulated herein takes into account the real extent of the stability phenomenon. It gives a good assessment of approaching of working conditions to a dangerous state, better than in the case of stress approach that actually is applied in standard regulations.

b) Proposition of solutions ensuring the condition for realization of loading in the form of generalized force

A propositions of technical solutions that ensure transferring of the load in the form of generalized force that are presented. Such solution causes that the loss of stability occurs with a higher eigenform and higher value of the critical force respectively. Increasing of the load-bearing capacity of the structural element, reduces the cost of its production and improves conditions of its safe use. The considered modifications of supporting conditions, are predicted for application in civil as well as mechanical in engineering solutions for structures, machines and vehicles.

The questions undertaken in the monograph were treated in the following publications and conference presentations

A. Stability of prismatic rods

1. Imiełowski Szymon: Sub-critical deformation of slender elements of bridge structure, Roads and Bridges - Drogi i Mosty, 2019 /in print/

2. Imiełowski Szymon: Stiffness of the compressed prismatic bars in the sub-critical range, in: Selected problems of construction, building materials and geotechnics / Dobiszewska M. (ed.), 2015, Publishing house of UTP University of Science and Technology, ISBN 978-83-64235-73-3, ss. 63-68

2. Ziółkowski Andrzej, Imiełowski Szymon: Buckling and Post-buckling Behaviour of Prismatic Aluminium Columns Submitted to a Series of Compressive Loads, w: Experimental Mechanics, vol. 51, nr 8, 2011, ss. 1335-1345,

3. Imiełowski Szymon, Ajdukiewicz Cezary Witold, Glinicka Aniela Maria: Experimental analysis of post-critical behavior on example of metal columns, in: Logistyka, nr 3, 2011, ss. 943-948

4. Imiełowski Szymon, Glinicka Aniela Maria, Ajdukiewicz Cezary Witold: Experimental buckling path of compressed bars under displacement control, in: Budownictwo i Architektura, vol. 13, nr 2, 2014, ss. 209-214

5. Imiełowski Szymon: Sequence of deformation modes of commpressed columns in case of nonconservative and conservative systems, 2015, 14th German-Polish Workshop on dynamical Problems in Mechanical Systems, Wandlitz, Niemcy 2015, paper presented

6. Imiełowski Szymon: Directional stiffness in analysis of compressed prismatic columns, 2013, in: 52 Sympozjon Modelowanie w Mechanice, Ustroń 2013, paper presented

7. Imiełowski Szymon, Odorowicz Jerzy, An original approach to buckling of beam/columns under conservative loading, 3rd International Conference on Integrity, Reliability & Failure, IRF'2009, Porto, Portugalia, 78-79, 20-24.07.2009

8. Imiełowski Szymon: Modal forms of columns subject to generalized follower force, in: Theoretical foundations of civil engineering. Polish-Ukrainian transactions / Szcześniak Wacław Edward (ed.), vol. 10, nr 1, 2, 2002, Oficyna Wydawnicza Politechniki Warszawskiej, ISBN 5-7763-8880-5, ss. 141-150

B. Non-conservative and pseudo-conservative systems

9. Imiełowski Szymon, R. Bogacz, Stability constraints in optimization of cracked columns subjected to compressive follower load, Engineering Transaction, v.55, z.4, 277-288, 2007

10. Imiełowski Szymon, R.Bogacz, W.Kurnik, Fixed point in frequency domain of structures subject to generalized follower force, Machine Dynamics Problems, v.25, 169-182, 2001

11. Bajer Czesław, Bogacz Roman, Imiełowski Szymon: Passive Control of a Beam Subject to Travelling Inertial Load, w: Engineering Transactions (Rozprawy inżynierskie), 2000, ss. 283-292

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13. Imiełowski Szymon, Bogacz Roman: Coexistance of divergence and flutter features of nonconser vative system on example of railway wheelset, w: Dynamical Problems in Mechanical Systems, Eds. R.Bogacz, G.P. Ostermayer i K.Popp. , 23-30, Warszawa 1996

5. Discussion on other scientific and research achievements

a) Research on water hammer phenomenon

Water hammer is one of the exceptional loads exerted on pipeline installations. It is the phenomenon of a sudden change of fluid or gas pressure in the pipe, that appears due to quick closing or opening of the valve, pump failure, sudden switch-off of electricity, etc. The phenomenon is very unfavorable and can cause a pipe damage by creation plastic zones, cracking of the pipe, unsealing of connections between pipeline elements as well as by launching excessive vibrations of the pipe. In the articles examples of methods and devices for protection of the structure against water hammer are presented as well as:

- An original method for assessing of the effectiveness of the devices for suppression of water hammer wave was proposed. Effectiveness of different methods and devices for protecting the structure against water hammer was evaluated with the use of this method.

- An original device for protection of a pipeline against the water hammer was proposed, in which the principle of operation of a dynamic vibration eliminator is applied. The solution is submitted to the Patent Office.

The results of theoretical and experimental research indicate that the use of such eliminator in the water supply system is an effective device for protection of pipelines against water hammer effects. A properly designed eliminator effectively reduces the maximum amplitudes of the hydraulic shock pressure and shortens the time of the entire phenomenon. The parameters of the dynamic vibration eliminator were determined. In the Department of Hydro-Engineering and Hydraulics a prototype device was built and experimental verification of the eliminator model was performed. A patent application has been submitted.

From September 2016, I am the auxiliary promotor of doctoral student M.Sc. Bartosz Śniegocki. His dissertation "Assessment of the possibility of damping of the hydraulic shock wave with the use of a dynamic vibration eliminator" is finished and has submitted to review. The work is proceeded at the Department of Building Installations, Hydrotechnics and Environmental Engineering, with the supervisor prof. dr hab. Marek Mitosek.

The second kind of activity relating to this topic is an analysis of the pipelines walls strength in water hammer conditions. In cooperation with the Faculty of Civil Engineering of

Warsaw University of Technology, a series of laboratory tests was carried out at dynamic load simulating hydraulic impact conditions.

- Variation of Young's modulus due to action of water hammer, were determined for materials used for the production of hydraulic conduits, namely: HDPE, MDPE polyethylenes and PVC.

List of publications and conference presentations on the water hammer phenomenon

1. Kubrak Michał, Kodura Apoloniusz, Imiełowski Szymon Bogdan: Analysis of Pressure Wave Velocity in a Steel Pipeline with Inserted Fiber Optic Cable, w: Free Surface Flows and Transport Processes / Kalinowska Monika B., Mrokowska Magdalena Maria, Rowiński Paweł (red.), GeoPlanet: Earth and Planetary Sciences, 2018, Springer International Publishing, ISBN 978-3-319-70913-0, ss. 281-292
2. Imiełowski Szymon Bogdan, Śniegocki Bartosz: Protection of pipeline Bridges against vibrations caused by a water hammer, w: Roads and Bridges – Drogi i Mosty, vol. 16, nr 1, 2017, ss.65-79
3. Imiełowski Szymon Bogdan, Śniegocki Bartosz: Methods of the pipeline bridges protection against the effects of water hammer, w: Czasopismo Inżynierii Lądowej i Wodnej, Środowiska i Architektury, JCEEA, vol. 64, nr 3/I, 2017, ss. 417-425, DOI:10.7862/rb.2017.134
4. Imiełowski Szymon Bogdan, Śniegocki Bartosz: Protection of pipeline Bridges against vibrations caused by a water hammer, w: Roads and Bridges – Drogi i Mosty, vol. 16, nr 1, 2017, ss.65-79, DOI:10.709/rabdim.017.005
5. Imiełowski Szymon, Kodura Apoloniusz, Glinicka Aniela Maria, Ajdukiewicz Cezary Witold: Experimental Study on Mechanical Properties of Polyethylene HDPE in Conditions of Hydraulic Impact Simulation, w: 26th Symposium on Experimental Mechanics of Solids. Selected, peer reviewed papers from the 26th Symposium / Pyrzanowski Paweł, Gadomski Jacek (red.), Solid State Phenomena, vol. 240, 2016, Tran Tech Publications Ltd, ISBN 978-3-03835-568-7, ss. 149-154, DOI:10.4028/www.scientific.net/SSP.240.149

b) Research on the load capacity of corroded bars

The thin-walled columns are often applied in building, rail and road constructions. This portion of work involved analysis of the load bearing capacity of axially compressed thin-walled corroded steel bars. The surface corrosion is distributed uniformly or in a selected areas of the column wall surfaces. Volume losses due to development of corrosion reduce the cross-section of the column wall and affect their bearing capacity. The theory of thin-walled bars was used for calculations. Computational models of column corrosion defects were assumed on the base of observation of existing corroded structures. In each study, several models of wall weakening due to corrosion defects have been considered on example of selected thin-walled profiles.

Results of theoretical analysis on stability of corroded compressed thin-walled columns were illustrated by diagrams of load bearing capacity variation caused by corrosion defects.

- Reducing of load capacity due to corrosion growth, as well as the change of the buckling mode were observed in the analyzed cases. The corrosion development that causes an asymmetric loss of thickness is usually more dangerous, because can affect the change of buckling mode. The change of the buckling mode from flexural to flexure-torsional was observed in the analyzed models.

List of publications and conference presentations on the load-bearing capacity of corroded bars

1. Glinicka Aniela Maria, Ajdukiewicz Cezary Witold, Imiełowski Szymon: Effects of uniformly distributed side corrosion on thin-walled open cross-section steel columns, in: Roads and Bridges - Drogi I Mosty, vol. 15, nr 4, 2016, ss. 257-270, DOI:10.7409/rabdim.016.016
2. Glinicka Aniela Maria, Imiełowski Szymon, Ajdukiewicz Cezary Witold: Influence of uniformly distributed corrosion on the compressive capacity of selected thin-walled metal columns, w: Procedia Engineering, vol. 111, 2015, ss. 262-268, DOI:10.1016/j.proeng.2015.07.087
3. Glinicka Aniela Maria, Imiełowski Szymon: Assessment of load-bearing capacity changes of steel columns in passageways due to corrosion, in: Current issues of communication construction, Jubilee Edition on the occasion of the 75th anniversary of Professor Wacław Szcześniak; Zbiciak Artur, Ataman Magdalena (eds.), 2015, Faculty of Civil Engineering of Warsaw University of Technology, ISBN 978-83-7814-481, ss. 71-80
4. Glinicka Aniela Maria, Imiełowski Szymon: Influence of the cross-section modification of corroded struts on bearing capacity, in: Logistyka, nr 4, 2015, ss. 3411-3416 CD 2

c) Publication on the structural reliability

This article follow my activity in the Technical Committee ISO TC98 "Bases for design of structures".

1. Chmielewski Tadeusz, Imiełowski Szymon: Bases for design of railway engineering structures based on risk and reliability assessment according to ISO standards, in: Railway engineering - opportunities and challenges, Materials of the 64th Scientific Conference of the Civil and Water Engineering Committee of the Polish Academy of Sciences and the Science Committee PZITB Krynica 2018, Publishing House Cracow University of Technology, ISBN 978-83-909811-5-4, pp. 77-102

6. Information on didactic and popularizing achievements, international cooperation and cooperation with economy units is included in a separate study "List of habilitation achievements"

7. Summary of bibliometric data

No.	Type of work	Number of articles	MNiSW points all /my share	Summary IF
1.	Articles in the JCR base	7	162 / 81,9	5,175
2.	Publications in magazines listed in the MNiSzW database	22	174 / 98,73	
3.	Chapters from the book series	4	40 / 16,6	
4.	Chapters in monographs	2	20 / 4,5	
5.	Publications as conference materials	5		
6.	Manual, script, prescript	1 + 1 + 1	75 / 30	
7.	Presented papers at national (7) and international (22) conferences	27		
	Suma	**43 + 27**	**471 / 231,7**	