Editorial of the special issue on stability and nonlinear analysis of steel structures

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EDITORIAL OF THE SPECIAL ISSUE ON STABILITY AND NONLINEAR ANALYSIS OF STEEL STRUCTURES

Stability of Structures, definitions and terminology

Scientifically, buckling is a mathematical instability, leading to a failure mode. The formal meaning of the notion is found in engineering and sciences, concerning stability of systems. Broadly speaking, structural stability can be defined as capacity of a slender structure to recover equilibrium.

Stability is an essential requirement for all structures. Theoretically, for a structural system, buckling is caused by a bifurcation in the solution to the equations of static equilibrium. At a certain stage under an increasing load, further load is able to be sustained in one of two states of equilibrium: an undeformed state, or a laterally-deformed state. In practice, buckling is characterized by a sudden failure of a structural member subjected to high compressive stress, where the actual compressive stress at the point of failure is less than the ultimate compressive stresses that the material is capable of withstanding. Failure occurs in a distinct direction compared to the direction of the applied load.

To evaluate the behaviour of a slender structure which might lose its stability according to the previous definition, three characteristic ranges of the load-deformation behaviour should be considered:

– the pre-critical range , i.e. $P \in (0, P_{cr}]$ defining the domain of *Structural stability*;

– the critical point (bifurcation of equilibrium), $P = P_{cr}$;

– the post-critical range, i.e. $P > P_{cr}$ the *Structural instability* domain.

Since metal structures, steel in particular, are slender, they are most prone to instability problems; hence the research on steel structures focussed on stability.

Although the stability of bars was first studied over 250 years ago (Euler's paper was published in 1744), adequate solutions are still not available for many problems in structural stability. So much has been and is being studied and written in the field of structural stability, that one may well wonder why, after such intellectual and financial efforts, there are no definite solutions to these problems. Numerical facilities and advanced FE codes make it possibly today to calculate and/or simulate accurately the behaviour of complex structures. However, for slender structures highly sensitive to buckling, there are still difficulties for a reliable evaluation of its stability.

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This is because determining the load under which a structure collapses due to the loss of stability still remains one of the most sensitive problems of structural design. This is due to the following factors (Gioncu, 2005):

a) The loss of stability depends on numerous factors, some of which are very difficult to control. This is confirmed by a number of recent structure accidents. Faulty design and execution, overstressing or the use of inadequate materials have been shown to be mainly responsible for these accidents. It should be noted that these accidents practically cover the entire range of structures. Today, only a specialist can carry out stability checks in complete agreement with the actual behaviour of the structure.

b) Instability occurs in a region with both strong geometrical and material nonlinearities. For the pre-critical range an extensive literature provides effective solutions. For the post-critical range, the theoretical background was significantly developed within the second half of the last century, but only after remarkable progress in the field of electronic computing equipment, and non-linear analysis using the Finite Element Method, FEM (e.g. GMNIA- Geometrical and Material Nonlinear Analysis including Imperfections) and after the development of some special numerical techniques (e.g. the Arc-Length Method) in the neighbourhood of the limit point. These developments made it possible to describe correctly the behaviour of structure, shortly before its failure, and after. However, such analyses are difficult and costly and they are not accessible for many designers.

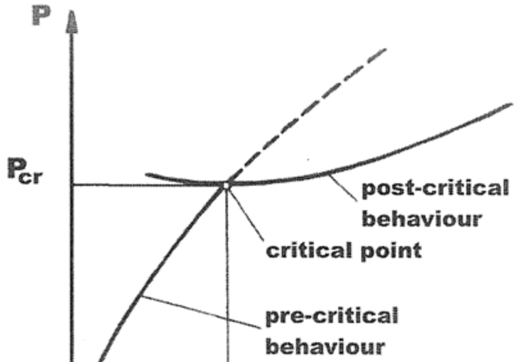

Fig. 1 Critical and Post-Critical behaviour.

c) In no other field of structural mechanics, the influence of imperfections due to the execution is as significant as in the field of instability. In strength analysis the stress-strain state is determined by means of an idealized scheme of the structure where neglecting the geometrical and mechanical imperfections leads to relatively small differences in failure load. In the case of instability on the other hand, failure loads are influenced to a large extent by imperfections so that they cannot be neglected.

d) Checking the buckling resistance of structures experimentally is very difficult, because it is impossible to test the actual structure just until it collapse. In strength analysis, reduced model tests are used for checking the validity of theoretical values. In stability analysis, testing on reduced models is irrelevant in most cases, because a correct modelling of the effect of imperfections is practically impossible.

e) There is a wealth of information available in numerous papers dealing with the stability and instability of structures, but information available in design codes and standards is limited, even in Eurocode 3. In this situation structural designers may commit grave errors in the structural instability checking.

Selected historical milestone references

Structural stability has a long history. One says (Elishakoff, 2000), the first description of an instability phenomenon goes to the Bible, where the Tower of Babel lost its stability under its own weight (610 B.C.). According to Godoy (2000) „*perhaps the first to investigate structural stability using theoretical tools were the Greek masters between 400 B.C. and 200 B.C. Aristotle (384 B.C.–322B.C.) employed kinematics concepts to study changes in stationary systems; and Archimedes (287 B.C.–212 B.C.) used geometric methods to assess the stability of floating bodies*”.

So, even it is unanimously recognised that mathematically the theory of stability was initiated by the Swiss mathematician, Euler in 1744 formulated structural stability in a mathematical way but technically speaking, stability as structural phenomenon dates from long before Euler.

Heron of Alexandria (about 100 B.C.), in the course of a ‘long dull work on static’s’ endeavoured to explain why the strength of a piece of wood reduces as its length increases (Villagio). Leonardo da Vinci (1452–1519) provided two empirical rules for the strength of columns in compression. The Jesuit Mersenne (1588–1648), in his Reflexiones on the causes of resistance in solids, observed that ‘iron, copper and other metals, even single bodies, when subject to a force or weight, curve and bend to the form of an arch before breaking’ (Benvenuto). Mersenne’s conclusions were unexpectedly confirmed by the consistent programme of experiments conducted by Van Musschenbroek (1692–1761), the inventor of testing machines designed to allow systematic variation of experimental parameters. Van Musschenbroek even proposed a quantitative law for the failure in compression of a parallelepiped composed of wood. But the greatest achievement in the period preceding Euler was made undoubtedly by Bernoulli (1654–1705). Bernoulli, as distinct from Galileo and Mariotte, ignored the resistance of beams and instead considered their deflection. He was able to construct the equation of a flexible bar deformed in the plane considering finite deflection and a nonlinear (parabolic) dependence between curvature and bending moment. This enabled Euler to find the well-known today's formula of elastic critical load of a compression bar. Lagrange (1736–1813) developed Euler's theory, generalizing it to columns of variable cross-section, and used it for checking the most stable shape of compressed columns. He introduced the notion of bifurcation that connects linearized and fully nonlinear solutions.

Euler's theory found its applications only from the 19th century under the pressure of practical problems raised by industrial and building development when most problems of structural stability were basically linear elastic. The twentieth century has witnessed a great expansion of the stability theory into nonlinear behaviour, caused either by large defections or by nonlinearity of the constitutive law of the material. In the second half of this century, dynamic stability, important especially for non-conservative systems, became reasonably well understood.

A selective review of some milestones of these developments reads as follows:

Young treated the lateral buckling of a column with variable cross-section; Navier derived the correct differential equation for a thin plate subject to uniform compressive forces; Kirchhoff proposed an elegant theory for slender rods experiencing large displacement and small strain; Euler's theory was applied to thin shells; Föppl and von Kármán derived a system of two equations describing the large deflection of a thin plate with stresses acting in the middle plane; Reissner relaxed some of the simplifying assumptions of Föppl and von Karman theory.

At the end of the 19th century there was general agreement that a unified theory of structural stability, to generalize and give a framework to all previous results, has to consider instability as a dynamic problem. The development of this idea really starts with the contributions of Poincaré (1854–1912) who discovered a general method for dynamic systems involving series proved convergent for all values of time, and who achieved consistency with the studies by Lyapunov (1857–1912). In simple terms, if all solutions of the dynamical system that start out near an equilibrium point x_e stay near xe forever, then x_e is *Lyapunov stable*. More strongly, if x_e is Lyapunov stable and all solutions that start out near x_e converge to x_e, then x_e is *asymptotically stable*. The notion of *exponential stability* guarantees a minimal rate of decay, i.e., an estimate of how quickly the solutions converge. The idea of *Lyapunov stability* can be extended to infinite-dimensional manifolds, where it is known as structural stability, which concerns the behaviour of different but "nearby" solutions to differential equations.

Based on *Lyapunov stability* theorems, in 1945 Koiter has published his Ph.D. thesis describing a general theory for the stability of elastic systems subject to conservative loadings. His work contained also a rigorous confirmation of the effect of initial imperfections on the buckling load of axially compressed shells. Koiter's general theory of elastic stability has marked the beginning of the

Imperfection Sensitivity Design Philosophy. In fact, it employed bifurcation theory in continuum systems. In the new approach, the information given by critical loads was seen as insufficient, and Koiter employed perturbation theory to develop an asymptotic analysis that allowed him to follow the post-buckling path in its early stages (Elishakoff, 2005). While Euler was the first to give a formula for the critical load of an ideal structure, Koiter was the first to give one for an imperfect structure.

Today, the highly theoretical method of Koiter is numerically implemented through the Finite Element Method enabling to model complex interactive stability modes – one of the papers in the present volume is dealing with that.

International framework of scientific cooperation in the Structural Stability domain

Professor Beer from the Technical University of Graz had the idea to organize in 1971 an International Colloquium in order to compare the ECCS (European Convention of Constructional Steelwork) approach of buckling curves of the slender bars in compression, just recently launched in EU countries, with those applied in Eastern Europe, the United States of America and Japan. This Colloquium was organized in Paris in 1972, followed in 1974, in London covering the assembly of structural stability problems. There, Sfintesco as President of ECCS and Beedle, as Chairman of SSRC (Structural Stability Research Council, USA) have proposed to enlarge both the topic and geographical areas of this Colloquium and transform it in a traveling event. A long series of colloquia under the coordination of the SSRC has started, the last one, the 21st, being organized in Rio de Janeiro; the next and 22nd one is planned to take place in Timisoara, Romania in 2016. At the 1997 edition, in Nagoya, the general framing topic "*Stability of Steel Structures* "was enlarged and became "*Stability and Ductility of Steel Structures*" – SDSS. Previous editions of October 1982 and September 1999 have been organized by the Politehnica University of Timisoara in cooperation of Romanian Academy, the Timisoara Branch, through the Committee for Structural Stability.

In parallel with the SSRC series, in October 1992 in Timisoara, another series of conferences started, dedicated to Coupled Instabilities in Metal Structures. This CIMS series has a recurrence period of four years: the last and 6th one being organized in Glasgow in December 2012 after the 5th in 2008 in Sydney, while the next and 7th CIMS conference is expected to take place in Baltimore in the Autumn of 2016.

In Europe, the organization offering an integrating framework for the research activity related to steel structures is ECCS – European Convention for Constructional Steelwork, founded in 1955. Outstanding European scientists and engineers, from academia, research centers and industry are taking part in the Technical Committees (TC-s) of ECCS, which are playing an important role in technical and scientific forums and working groups contributing to developing and promoting advanced knowledge in the field of steel structures. Among other ECCS TC-s, there is the TC 8 on Structural Stability. Along the years TC8 has contributed to the elaboration of European Buckling Curves (1970), the ECCS Manual on Stability of Structures (1976), Behavior and Design of Plated Structures (1986), the 5th editions starting in 1980 of the Recommendations for Stability of Steel Shells, and in last two decades to the provisions for Structural Stability Design of Eurocode 3- Design of Steel Structures (EN 1993-1-1, EN 1993-1-5, EN 1993-1-6).

This Special Issue is in good part the result of ECCS TC8 cooperation, 9 from the 12 papers being authored by the members of this Group.

Present Special Issue on “Stability and nonlinear analysis of steel structures”

The topics of the papers included in this volume are diverse enough, tackling stability problems of steel structures with thin and tick walled bar members, open and hollow sections, plated structures and curved sandwich panels. There are theoretical, numerical and experimental approaches and combinations of them used in solving stability problems. The 12 papers have been framed into two parts:

Part I: Theoretical background, numerical and experimental advanced studies – 7 papers;

Part II: Design codification oriented studies – 5 papers.

36 authors from 11 European Countries have contributed with their research works to this Special Issue of the Romanian Journal of Technical Sciences. We are expressing our gratitude to all of them.

We are also grateful to the reviewers for the time and effort they spent evaluating the papers.

Thanks are also due to Dr. Luigi VLADAREANU and Dr. Dan DUMITRU of Institute of Solid Mechanics of the Romanian Academy, Bucharest, for the editorial work.

The guest editors hope that this special issue gives an overview of current research activities contributing to the stability and nonlinear analysis of steel structures.

Timişoara, August 2014

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