MINISTERUL EDUCAȚIEI, CERCETĂRII, TINERETULUI ȘI SPORTULUI

UNIVERSITATEA TEHNICĂ
DIN CLUJ-NAPOCA

ADVANCED NONLINEAR ANALYSIS TECHNIQUES WITH APPLICATIONS IN STRUCTURAL AND GEOTECHNICAL ENGINEERING

HABILITATION THESIS

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Abstract

The latest hard and soft computer developments have opened new opportunities to describe the complex behaviour of real structures based on *advanced nonlinear inelastic analysis techniques*.

The present thesis represents a summary of the research achievements of author, undertaken in the period between 2002 and 2013, on advanced nonlinear analysis techniques with applications in structural and geotechnical engineering. During the decade mentioned above, the research and professional interests, of the author of this thesis, have been focused on improving the structural computational methods for design of civil structures. The research includes both computational and experimental techniques with emphasis on the development and application of advanced nonlinear analysis of structural limit states, push-over analysis for seismic performance evaluation of structures, finite element simulation of composite materials subjected to extreme loads such as ballistic impact and explosions, design and behaviour of composite steel-concrete structures, and also for application of FEM for geotechnical problems.

Much of the research work has been dedicated to advanced nonlinear analysis of frame structures able to describe the complex behaviour of 3D steel and composite steel-concrete frame structures with a minimum computational effort. Some of these works are important contributions for the prediction of the structural behaviour of frame structures up to and beyond the structural collapse subjected to earthquake loads. The author of this thesis proposed a conceptually simple nonlinear inelastic analysis procedure aimed to be easy to use

in practical applications. Development of an integrated system for advanced structural analysis and seismic performance evaluation of 3D steel and composite steel-concrete building frameworks with rigid or flexible connections is described in the following research articles [1,2,3,4] and the book [5]. The advanced non-linear inelastic static analysis developed uses the accuracy of the fiber elements approach for inelastic beam-column evaluation and address its efficiency and modelling shortcomings both to element level, through the use of only one element to model each physical member of the frame, and to cross-sectional level through the use of path integral approach for numerical integration of the cross-sectional nonlinear characteristics. These are essential requirements to approach real large spatial frame structures. The proposed software is presented as an efficient, reliable tool, ready to be implemented into design practice for advanced analysis and pushover analysis of spatial frame structures. The example of computations and the comparisons made have proved the robustness, accuracy and time saving of the proposed analysis method. The comparative studies shows that the proposed numerical method [1,2,3,4,5] and the computer program developed NEFCAD (http://www.cosminchiorean.com/software.html.) compares very well to exact plastic zone solution with much less computational effort than a fiber-finite element analysis.

Another significant result represents his contribution to ultimate strength analysis and design of composite-steel concrete cross-sections with arbitrary shapes subjected to biaxial bending and axial force. The procedures may be used to assess the main features of elasto-plastic behaviour of cross-sections subjected to biaxial bending and axial force: multiple yielding points, inelastic flexural and axial rigidity, moment-curvature relationship, and 3D failure surfaces. Furthermore the procedures allow cross-sections to be designed by solving directly for the reinforcement required to provide a cross-section with adequate strength. His studies in this field [5,6,7,8] reveals that near the axial load capacity under pure compression, when the strain softening of the concrete is taken into account, the solution is not unique which implies non-convexity of the failure surface in these situations. This aspect is a novelty in this field of research and explains why the majority of the numerical algorithms developed by other researchers fail to converge. Moreover, comparing the algorithm and the computer program developed by the author in [5,6,7,8] to determine the interaction diagrams and moment capacity contours of composite cross-sections, with the existing methods, it can be concluded that the proposed method is general, it is fast, convergence is assured for any load case, even near the state of pure compression or tension and is not sensitive to the initial/starting values, to how the origin of the reference loading axis is chosen or to the strain softening effect for concrete in compression. Due to presence of residual stresses, for encased steel section, a reduction of capacity strength of composite steel-concrete cross-section was observed. The influence of residual stresses on the carrying capacity of cross- sections is most important with higher axial load levels. It may be concluded that the influence of the residual stress on the carrying capacity and inelastic behavior during the loading process is important and must be considered in the valuable advanced analysis of composite cross-sections.

Another avenue of his research work is in dynamic analysis of composite laminated plates subjected to extreme loads such as ballistic impact. A combined numerical and experimental study was developed on the behaviour of composite plates reinforced with aramidic fibres, with and without an additional protective layer of polymeric mortar, under normal impact with projectiles at moderately high speeds. Experimental and numerical simulation of ballistic impact problems on thin composite laminated plates reinforced with Kevlar 29 was reported in [9]. For high velocity impact where the impactor penetrates the panel completely and exits with a residual velocity, to the author's knowledge, only two contributions (one of them being

signed by the author of this thesis) are available in international literature on numerical modelling of a fully penetrated impact process of a laminated composite panel [9]. The importance of this finding is certified by the high number of citations of the paper [9].

In the last decade, the author has published over 40 papers in refereed journals and conference proceedings and has authored a book entitled ―*Software applications for nonlinear analysis of 3D frame structures* [5] (in Romanian). He is also the main developer of a FE software package GFAS (A finite Element System for Geotechnical Applications) [10] a product of Geostru Corporation (www.geostru.com) http://www.cosminchiorean.com/software.html.

The author serves in several scientific committees and is a reviewer for several major international journals including: *Engineering Structures* (Elsevier); *Computers & Structures* (Elsevier); *Advances in Engineering Software* (Elsevier); *Composite Structures* (Elsevier); *International Journal of Steel and Composite Structures* (Techno Press Publisher, Korea), *Structures and Building* (Institution of Civil Engineering) and also serves as editorial board member of the *Open Civil Engineering Journal* (Bentham Science Publisher http://www.benthamscience.com/open/tociej/index.htm) and is Editor-In-Chief of the National Journal: *Acta Technica Napocensis:Civil Engineering and Architecture* (http://constructii.utcluj.ro/ActaCivilEng/). The author serves as a editorial board member of *International Conference on Computational Structures Technology* (CST) http://www.civil-comp.com/conf/ and is member of the following associations and societies: SigmaXi-The Scientific Research Society (http://www.sigmaxi.org/); *International Society for Soil Mechanics and Geotechnical Engineering (ISSMGE) Member of the Technical Committee: Numerical Methods in Geomechanics*, 2009-2013 (http://www.issmge.org/web/page.aspx?sid=4137); The author is member of the Civil Engineering Panel in framework of the POSDRU Project called ―Doctorate in Universities of Excellence-Research Assessment and Support for Scientific Publishing (www.cncsis.ro), he has been involved as a PhD reviewer in over 20 PhD theses and he also coordinated over 30 MSc theses. Currently he is the head of Structural Mechanics Department from Technical University of Cluj-Napoca and member of *National Research Council* (CNCS), Engineering Science Panel.

This thesis is divided into two main parts. The first part concerns in an overview of the research significance and achievements (Chapter 2) whereas in the second part (Chapter 3) the future research and plans of career development are briefly outlined. Chapter 1 summarise the main findings of the author in the field of nonlinear analysis of structures and in the last chapter (Chapter 4) the main publications of the author and the main references associated to the chapters 2 and 3 are presented. The overview part of the thesis is outlined in the form of four main chapters in which the main research achievements are presented in the context of state of the art in the field. Section 2.1 describes the advanced numerical procedures developed by the author for nonlinear inelastic analysis of composite steel-concrete cross-sections with arbitrary shapes subjected to biaxial bending and axial force [5,6,7,8]. Section 2.2 presents an integrated system for advanced structural analysis and seismic performance evaluation of 3D steel and composite steel-concrete building frameworks with rigid or flexible connections [1,2,3,4,5]. Section 2.3 describes a combined numerical and experimental study developed on the behaviour of composite plates reinforced with aramidic fibres, with and without an additional protective layer of polymeric mortar, under normal impact with projectiles at moderately high speeds [9]. Section 2.4 presents the main features of the program GFAS (A finite element system for geotechnical applications) [10] a finite element

package that has been developed, by the author of this thesis, specifically for the analysis of deformation and stability analysis in geotechnical engineering problems.

The future research and development activities, of the author of this thesis, will be focused further on application of advanced nonlinear techniques to describe the complex behaviour of real large-scale structures with emphasis on the following topics: *Advanced pushover analysis of 3D composite steel-concrete frameworks; Advanced numerical modelling of real-large 3D frameworks. Benchmarks for steel and composite steel-concrete structures*; *Advanced nonlinear dynamic analysis of 3D frame structures*; *Computer automated optimal structural design in seismic zones based on structural performance criteria*.

The author's research would not have started and continued without help and support of many colleagues from Department of Structural Mechanics, Technical University of Cluj Napoca, especially by Prof. G.M. Barsan. Their support and advice is gratefully acknowledged. The research associated to dynamic analysis of composite laminated plates was started during a postdoctoral stage of the author of this thesis at Department of Civil Engineering (DEC), New University of Lisbon (UNL), Portugal. The support of my friends and colleagues from UNL-DEC, Prof. C Cismasiu and Prof. M.A.G. Silva is gratefully acknowledged. The author gratefully acknowledges the financial support from Geostru Software, Mr. Filipo Catanzarati, for development of the finite element package GFAS.

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