University of Kragujevac

Faculty of Engineering

To: Teaching and Scientific Council
Faculty of Engineering

Subject: Report of the Commission for assessing the thesis written part and the oral public defense of the Vladimir Dunić doctoral dissertation

By the decision of the Teaching and Scientific council of Faculty of Engineering University of Kragujevac no. 01-1/475-6 from 19.02.2015., we are appointed as members of the Commission for assessing the thesis written part and the oral public defense of the Vladimir Dunić doctoral dissertation under title:

DEVELOPMENT AND IMPLEMENTATION OF THERMO-MECHANICAL CONSTITUTIVE MODEL FOR NUMERICAL ANALYSIS OF SHAPE MEMORY ALLOYS

After the insight to the prepared doctoral dissertation and the Report of the Commission for assessing the eligibility of the candidate Dunić Vladimir and the doctoral dissertation, approved by the Decision of the Faculty of Engineering in Kragujevac no. 01-1/2136-4 from 10.07.2014, according to University of Kragujevac Regulations on the application, preparation and defense of doctoral thesis, the Commission submits to the Teaching and Scientific Council the next

REPORT

1. The significance and contribution of the doctoral dissertation from the aspect of the current situation in a particular scientific field

The doctoral dissertation of the candidate Vladimir Dunić, dipl. mech. eng., entitled "**Development and implementation of thermo-mechanical constitutive model for numerical analysis of shape memory alloys**" is the result of the candidate scientific research in the current field of science that deals with the analysis of shape memory alloys behavior. From the aspect of the research topic and the obtained results, this dissertation represents a unique scientific work.

The candidate has made a critical analysis and systematization of existing knowledge, experiences and scientific results of competent researchers in the field of research of this doctoral thesis. Based on the analysis of advantages and disadvantages of recently used approaches, methods and models in this area, the candidate has defined the subject and the purpose of his research.

The significance and contribution of this PhD thesis is related to the development and improvement of numerical algorithms, implementation, and application and simulation of thermo-mechanical behavior of shape memory alloys. Defined as The improvements are defined in order to improve the efficiency of numerical analysis in comparison with existing constitutive models. All variables are derived to depend on the effective values of stress, transformation strain and

martensitic volume fraction what allowed solving a nonlinear scalar equation at the level of integration points. Such constitutive model is used to solve problems which requires the application of the large strain theory using appropriate strain measures and their energy-conjugated stress measures. It also provided the simulation of shape memory alloys behavior with the influence of the structure strain rate. Thermo-mechanical coupling is provided and the dissipative energyis defined for the correct simulation of SMA behavior in terms of various strain rates. Accuracy verification is carried out through comparison to experimental results and the results from the literature which confirmed the functionality of a given approach.

2. The assessment that doctoral dissertation is the result of original scientific work of the candidate in the relevant scientific field

The commission finds that the doctoral dissertation of the candidate Vladimir Dunić, dipl. mech. eng., entitled **"Development and implementation of thermo-mechanical constitutive model for numerical analysis of shape memory alloys",** is the result of original scientific work. Analyzed topic is very relevant and important for the development of science in the field of shape memory alloys behavior. The candidate has elaborated the topic thoroughly and in detail, using the theoretical basis of scientific disciplines relevant to this issue. Numerous scientific papers are critically analyzed and evaluated relating to issues considered within this thesis.

The originality of scientific work, researach and the results obtained in the framework of this dissertation is reflected, among other things, in the following elements:

- Improvement of the constitutive model, compared to theory of prof. Lagoudas group, are achieved by modifying the thermodynamic force and state variables to depend on the effective values of stress, strain and martensitic volume fraction. The total stress is decomposed in deviatoric and mean part and the stress integration is carried out in the direction of deviatoric trial stress or trial transformation strain. This simplifies the constitutive model and the problem is reduced to a solution of a single scalar nonlinear equation in the iterative procedure.

- The candidate has recognized the need for simulation of thermo-mechanical behavior of SMA analyzing experimental tests which confirm the strong thermomechanical coupling during the pseudoelastic loading and unloading. He used this observation to improve the SMA constitutive model to simulate the thermo-mechanical coupled problems. He applied partitioned approach for modeling of complex stress and thermal states using FEM software. For verification of the implemented approach, the candidate modeled experiments with boundary and loading conditions for structural analysis and heat transfer. By comparing the experimental and numerical results, he showed good qualitative and quantitative agreement.

- The candidate has identified a need for simulation of complex stress states which occur in the exploitation of SMA structures, so he used multiplicative decomposition of the deformation gradient and hyper-elastic approach to expanded SMA constitutive model for solving the problems of large strains. He showed the ability to use an iterative procedure for small strain for large strain problems using appropriate strain measures and their conjugated stresses. The approach is verified through several examples of multi-axial loads.

3. An overview of the results of the candidate in a particular scientific field

Vladimir Dunić was born on December 09th 1983 in Pirot, Serbia. He completed his elementary education in 1998 in the elementary school "Jovan Popović" in Kragujevac with

excellent success. He continued his education at the First Kragujevac Gymnasium, where he graduated in 2002 as an excellent student.

He acquired professional title of graduate mechanical engineer at Faculty of Mechanical Engineering in 2008 with an average grade 9,27. He defended a diploma thesis entitled "Application of parallel computers in structural analysis" at the Department of Applied Mechanics and Automatic Control with a score of 10, after which he enrolled in doctoral studies at the same faculty. In the period of 2009-2011 he was a scholar of the Ministry of Science and Technological Development, Republic of Serbia. After that he was employed at the Faculty of Engineering as an associate in the Engineering software laboratory engaged on the projects of the Ministry of Science and Technological Development. From the beginning of the PhD studies, he has performed auditory exercises at home faculty on several subjects: Mechanics 2, Mechanics 3, Electrical engineering with electronics and Linear structural analysis. He is currently engaged in the implementation of two scientific projects of the Ministry of Education, Science and Technological Development of the Republic of Serbia: "Development of software for analysis of coupled multyphisics problems" TR32036, and "Application of Biomedical Engineering in Preclinical and Clinical Practice," III41007. In the past he has been involved in a project of the same Ministry: "Software development for explicit nonlinear dynamic analysis", TR12005. He also participated in the projects: Ministry of science and DAAD - Solving of multiphysics problems using software PAK - SOMUPAK, 2012-2013, TEMPUS - JEP 18114 -2003, Restructuring of Mechanical Engineering Studies, 09.2003 - 09.2006, FP6 RRSCD INNCODE 043 820, Reinforcement of Research Capacity in Software Development and Innovative Collaborative Design and Engineering in Serbia and Montenegro, 09.2006 -09.2008. During his studies, he also went on several international internship, including: stay in the period October 2006 - March 2007, during his studies at the Technical University of Braunschweig within TEMPUS - JEP 18114 -2003 and stay and collaboration with prof. dr. Elzbieta Pieczyska in August-September 2013 at the Institute of Fundamental Technological Research, Polish Academy of Sciences, Warsaw within the KMM-VIN scholarships.

PhD thesis topic entitled "**Development and implementation of thermo-mechanical constitutive model for numerical analysis of shape memory alloys**" was approved on 10.07.2014.

He published 17 scientific papers as an author or co-author (2 papers in top international journals, 1 paper in the journal of international importance, 5 international conference papers printed in a whole, 2 international conference papers printed in abstract, 1 paper in the journal of national importance, 6 national conferences papers printed in a whole) as follows:

Papers in top international journals [M21]

1. **Vladimir Dunić**, Elzbieta Pieczyska, Hisaaki Tobushi, Maria Staszczak, Radovan Slavković, Experimental and numerical thermo-mechanical analysis of SMA subjected to tension with various stress and strain rates, Smart Materials and Structures, Vol.23, No.5, pp. 055026 (11pp), ISSN 0964-1726, Doi http://dx.doi.org/10.1088/0964-1726/23/5/055026, 2014
2. Vladimir Milovanović, **Vladimir Dunić**, Dragan Rakić, Miroslav Živković, Identification causes of cracking on the underframe of wagon for containers transportation - Fatigue strength assessment of wagon welded joints, Engineering Failure Analysis, Vol.31, No.0, pp. 118-131, ISSN 1350-6307, Doi http://dx.doi.org/10.1016/j.engfailanal.2013.01.039, 2013

Paper in the journal of international importance [M23]

1. Elzbieta Pieczyska, Maria Staszczak, **Vladimir Dunić**, Radovan Slavković, Hisaaki Tobushi, Kohei Takeda, Development of stress-induced martensitic transformation in TiNi Shape Memory Alloy, *Journal of Materials Engineering and Performance*, Vol.23, No.7, pp. 2505-2514, ISSN 1059-9495, Doi http://dx.doi.org/10.1007/s11665-014-0959-y, 2014

International conference papers printed in a whole [M33]

1. Aleksandar Nikolić, **Vladimir Dunić**, Miroslav Živković, Radovan Slavković, Neutral file generation for GiD post-processing using PAK subroutines implemented in FEAP, 5th Conference On Advances And Applications Of GiD & 1st Kratos Workshop, Barcelona, Spain, 2010, May, pp. 17-20, ISBN 978-84-96736-90-0
2. Miroslav Živković, Marko Topalović, Radovan Slavković, **Vladimir Dunić**, Abaqus subroutine development and implementation for neo-hook hyperelastic matherial model, The 3rd International Conference of Serbian Society of Mechanics (IConSSM 2011), Vlasinsko Jezero, 2011, 05.07.-08.07., pp. 889-896, ISBN 978-86-909973-3-6
3. Radovan Slavković, Vukašin Slavković, Miroslav Živković, **Vladimir Dunić**, Stress integration for FCC crystal plasticity by finite element method, The 3rd International Conference of Serbian Society of Mechanics (IConSSM 2011), Vlasinsko Jezero, 2011, 05.07.-08.07., pp. 757-766, ISBN 978-86-909973-3-6
4. **Vladimir Dunić**, Nenad Busarac, Vukašin Slavković, Nenad Grujović, Miroslav Živković, Radovan Slavković, Partitioned thermo-mechanical coupling procedure of FEM components, Fourth Serbian (29th Yu) Congress on Theoretical and Applied Mechanics, Vrnjačka Banja, Serbia, 2013, 4-7 June 2013, pp. 517-522, ISBN 978-86-909973-5-0
5. **Vladimir Dunić**, Radovan Slavković, Nenad Busarac, Vukašin Slavković, Miroslav Živković, Implicit integration method of Shape Memory Alloys constitutive model, SEECCM III, 3rd South-East European Conference on Computational Mechanics, Kos Island, Greece, 2013, 12.06.-14.06., pp. 348-357, ISBN 978-960-99994-4-1

International conference papers printed in abstract [M34]

1. **Vladimir Dunić**, Radovan Slavković, Nenad Busarac, Vukasin Slavković, Miroslav Živković, Implicit stress integration method of Shape Memory material model, GAMM - 84th Annual Meeting of the International Association of Applied Mathematics and Mechanics, Novi Sad, Srbija, 2013, 18.03.-22.03., *Proc. Appl. Math. Mech.* pp. 151-152, ISBN 1617-7061, Doi http://dx.doi.org/10.1002/pamm.201310071
2. **Vladimir Dunić**, Elzbieta Pieczyska, Nenad Busarac, Radovan Slavković, Vukašin Slavković, Partitioned Thermo-Mechanical Coupling of SMA Constitutive Model, 39th SOLID MECHANICS CONFERENCE, Poljska, Zakopane, 2014, 01.09. - 05.09., pp. 255-256, ISBN 978-83-89687-89-0

Paper in the journal of national importance [M53]

1. **Vladimir Dunić**, Nenad Busarac, Dragan Rakić, Vukašin Slavković, Radovan Slavković, Miroslav Živković, Thermo-mechanical coupling procedure using partitioned approach - Application to arc welding simulation, *Journal of Serbian Society for Computational Mechanics*, Vol.6, No.1, pp. 29-44, ISSN 1820-6530, 2012

National conferences papers printed in a whole [M63]

1. Nenad Busarac, **Vladimir Dunić**, Miroslav Živković, Radovan Slavković, Petar Živković, Need for parallelization of FEM software, YuInfo2009 Conference, Kopaonik, 2009, March
2. **Vladimir Dunić**, Radovan Slavković, Nenad Busarac, Miroslav Živković, Application of external libraries in FEM software development, YuInfo2009 Conference, Kopaonik, 2009, March
3. Nenad Busarac, **Vladimir Dunić**, Radovan Slavković, Miloš Ivanović, Parallelization level analysis of the FEM software PAK, YuInfo2010 Conference, Kopaonik, 2010, March
4. Nenad Busarac, **Vladimir Dunić**, Miroslav Živković, Radovan Slavković, Analysis of MUMPS and PETSc solvers integrated in PAK software, YuInfo2011 Conference, Koponik, 2011, March
5. Nenad Busarac, **Vladimir Dunić**, Miroslav Živković, Radovan Slavković, Basic use of CTL middleware in PAK software, YuInfo2011 Conference, Kopaonik, 2011, March
6. **Vladimir Dunić**, Nenad Busarac, Vukašin Slavković, Radovan Slavković, Miroslav Živković, Performance analysis of FEM software on different computer architectures, YuInfo 2012, Kopaonik, 2012

4. Assessment of the scope and quality fulfillment with respect to the topic

The doctoral dissertation of the candidate Vladimir Dunić, dipl. mech. eng., entitled **"Development and implementation of thermo-mechanical constitutive model for numerical analysis of shape memory alloys"**, corresponds to the scope and content of the topic accepted by the Teaching and Scientific Council of the Faculty of Engineering and Expert Council of the University of Kragujevac. The thesis fully satisfy all scientific, technical and legal requirements for doctoral dissertation by quality, scope and results of research.

The research results in the written part of a doctoral dissertation are presented in a total of 158 pages. The thesis presents 67 graphic illustrations and 94 referenced papers. The content is divided into 10 chapters:

1. Introduction
2. Review and analysis of existing approaches to SMA models
3. Improved constitutive model for the analysis of SMA
4. Numerical implementation of SMA stress integration procedure
5. Thermo-mechanical coupling of structural and heat transfer analysis in SMA
6. Verification of coupled thermo-mechanical model by comparison to experimental results
7. Numerical analysis of problems and modeling of real SMA structures
8. Conclusions
9. Literature
10. Appendix

In Chapter 1 (Introduction) introduction is given in a form of short description of SMA properties and effect described in diagrams and figures. The phenomenological effects, thermo-mechanical behavior, properties and application of SMA are introduced.

In Chapter 2 (Review and analysis of existing approaches to SMA models), a review of the existing constitutive models have been discussed. The details about the SMA modeling approaches and the already established numerical procedures are analyzed and compared. A special case of thermo-mechanical experimental research and constitutive models capable to catch the SMA phenomena are discussed. The review of previous works has defined the demands and direction of research.

In Chapter 3 (Improved constitutive model for the analysis of SMA), the details about the constitutive SMA modeling are presented. Continuum mechanics and thermodynamic principles provide the base for the correct implementation of the free energy function. The details necessary for proper definition of strain along with the conjugated stress measures for the large strain theory are presented to ensure the extension of the small strain algorithm to large strain problems.

Chapter 4 (Numerical implementation of SMA stress integration procedure for small and large strain), concerns the details about the implementation of the stress integration procedure which ensures the previously presented theory to be easy incorporated into the Finite Element Method (FEM) program.

In Chapter 5 (Thermo-mechanical coupling of structural and heat transfer analysis in SMA), the algorithm for the partitioned thermo-mechanical coupling of the structural and heat transfer FEM program is presented with a details of implementation.

In Chapter 6 (Verification of coupled thermo-mechanical model by comparison to experimental results), the verification of the coupling algorithm is performed by the comparison of numerical simulation to the results obtained by experimental testing of the SMA. The curves of the stress and temperature change versus strain dependence are presented for the various stress and strain rates. The tests are carried out by the force and the displacement control what influences some differences in the SMA behavior analyzed in this chapter.

In Chapter 7 (Numerical analysis of problems and modeling of real SMA structures), firstly benchmark examples are defined as control tests of the implemented stress integration procedure. For the uniaxial loading examples the comparison to the literature results is presented. The investigation is extended by several multiaxial loading tests. The successful application of the presented theory is given on the selected realistic SMA problems.

In Chapter 8 (Conclusions), final remarks and conclusions noted during the research are presented. Further directions for the research and current challenges in this field are introduced.

У Chapter 9 (Literature) the referenced papers used during the research in the framework of the dissertation are given.

У Chapter 10 (Appendix), algorithm for the stress integration for the used SMA material model is presented.

5. Scientific results of the doctoral dissertation

The candidiate, Vladimir Dunić, dipl. mech. eng., in the framework of the dissertation, completed systematization of existing knowledge and experience in the field of numerical analysis of structures made of shape memory alloys. Within the thesis the candidate came to the results and conclusions that have their place and importance in scientific and practical sense. The most important scientific results of the doctoral thesis are:

- Improved constitutive model, with respect to the theory of the prof. Lagoudasa group, Texas A&M University, achieved by modifying the thermodynamic force and state variables to depend on the effective values of stress, strain and the martensitic volume fraction.

- Thermo-mechanically coupled solution able to simulate the behavior of SMA using the partitioned coupling approach for modeling complex stress and thermal states with the possibility of setting boundary conditions and loads for structural analysis and heat transfer

- The possibility to simulate thermo-mechanical behavior of materials under various loading rates for small and large strains using thermo-mechanical coupling

- The possibility to simulate complex stress states which occur during the exploitation of SMA structures by using the multiplicative decomposition of the deformation gradient and hyper-elastic approach to solve the problems of large strains.

6. The applicability and usefulness of the results in the theory and practice

The results of the doctoral dissertation of the candidate Vladimir Dunić, dipl. mech. eng. entitled **"Development and implementation of thermo-mechanical constitutive model for numerical analysis of shape memory alloys"** are applicable and useful in the theory and practice. A wide application of SMA in responsible structures, like stents implated in blood vessel, or other medical application (presented in the Introduction of dissertation) which requires high reliability during exploitation, as well as technical applications in high-responsible technical solutions (actuators in the aerospace industry, control of buliding, connecting pipes, etc.), as well as their high price, impose the need for most accurate simulation of thermo-mechanical behavior in order to increase reliability and reduce costs.

7. The way of presenting the results to the scientific community

Part of the scientific results, arising in the context of this dissertation, is presented by publishing scientific papers in international scientific journals and at international and national scientific conferences.

Practical aspects of realized scientific research were presented to domestic scientific and professional community through the realization of projects of the Ministry of Education, Science and Technological Development of the Republic of Serbia entitled "Development of software for analysis of coupled multyphisics problems" TR32036, and "Application of Biomedical Engineering in Preclinical and Clinical Practice," III41007.

The commission considers that the results of research and doctoral dissertation provide comprehensive and useful material for future publication in high-ranking international and national journals and scientific conferences dealing with problems SMA behavior

Based on all the above, the Commission issues the following

CONCLUSION

Doctoral dissertation of the candidate Vladimir Dunić, dipl. mech. eng., coresspons in scope and in quality to the approved dissertation topic, decision no. 01-1/2136-4 from 10.07.2014. by the Teaching and Scientific Council of the Faculty of Engineering in Kragujevac.

The candidate used a common and standardized technical terminology and structure of the doctoral thesis and methodology exposure are in accordance with university standards.

During his doctoral thesis preparation, the candidate Dunić Vladimir came to original research results, presented in the dissertation which represents a significant contribution to the field related to the implementation of complex constitutive models of SMA by the finite element method. The results has been partially published in several papers in international and national scientific journals and conferences.

The candidate has demonstrated that he can follow a methodology of scientific research and that he has systematic approach and the ability to access and use literature. At the same time, using their professional education and personal experience, he has shown the ability to comprehensively solve complex problems in order to define integrative conclusions in obtaining specific and applicable results.

Based on the foregoing, the commission for the assessment of written part and oral public defense of the doctoral dissertation of the candidate Vladimir Dunić, dipl. mech. eng., unanimously concluded that the doctoral dissertation, entitled

"DEVELOPMENT AND IMPLEMENTATION OF THERMO-MECHANICAL CONSTITUTIVE MODEL FOR NUMERICAL ANALYSIS OF SHAPE MEMORY ALLOYS"

completely satisfies all scientific, technical and legal criteria for doctoral dissertations in quality, scope and results of research. The commission is pleased to propose the Teaching and Scientific Council of the Faculty of Engineering in Kragujevac, on the basis of this report, acceptance of the doctoral dissertation as successful and to invite the candidate to the public, oral defense.

Commission members

dr. Radovan Slavković, Professor,
Faculty of Engineering, Kragujevac. Scientific fields: Applied Mechanics, Applied Informatics and Software Engineering

dr. hab. Elżbieta A. Pieczyska, Assoc. Professor,
Institute of Fundamental Technological Research, Polish Academy of Sciences , Warsaw;
Scientific fields: Mechanics , Resistance of materials and Plasticity

dr. Miroslav Zivković, Professor,
Faculty of Engineering, Kragujevac. Scientific fields: Applied Mechanics, Applied Informatics and Software Engineering

dr. Nenad Filipović, Professor,
Faculty of Engineering, Kragujevac. Scientific fields: Applied Mechanics, Applied Informatics and Software Engineering

dr. Aleksandar Sedmak, Professor,
Faculty of Mechanical Engineering, Belgrade, Scientific fields: materials , welding, structural integrity, fracture mechanics, computational fracture mechanics, materials testing

dr. Nenad Grujović , Professor,
Faculty of Engineering, Kragujevac. Scientific fields: Applied Mechanics, Applied Informatics and Software Engineering

In Kragujevac,
06.03.2015.