

Review of Doctoral Thesis

1. PhD candidate
Ing. Ondřej Červínek / Ondrej.Cervinek@vut.cz
2. Name of PhD programme
Design and Process Engineering (Mechanical Engineering Design)
3. Title of PhD thesis
Computational models for non-linear mechanical loading analyses of lattice structures made by powder laser bed fusion
4. Principal supervisor
doc. Ing. Daniel Koutný, Ph.D. / Daniel.Koutny@vut.cz
5. Co-supervisor
doc. Ing. David Paloušek, Ph.D. / david.palousek@one3d.cz
6. Reviewer
Dr. Michael R. Tucker / mtucker@ethz.ch
ETH Zurich
7. Overview of the scope of PhD thesis¹
Very good
<p>This thesis develops and evaluates new methods for predicting the plastic deformation behavior of additively manufactured metal lattice structures under low-to-moderate strain rates via finite element methods (FEM). As the thesis outlines, there is a gap in our understanding of how to model such gross deformation behavior, especially given the complexity of the lattice geometry and variability in the as-built structure. Models of beam lattice structures contain a number of elements and nodes that is far in excess of what a continuum representation of the same volume would contain, which when coupled with the number of degrees of freedom at the nodes, represents a significant computational challenge. Furthermore, it is known that the structural behavior of lattice structures is significantly different from solid structures. The geometric variability of the lattice structure inherent to the manufacturing process adds significant uncertainty. This thesis addresses these issues by introducing new methods for experimentally determining the mechanical properties of thin struts, development of enhanced non-linear models to account for the behavior of the lattice (including geometric imperfections), and verification of the models through experimental testing. As a result of this thesis, our ability to model and predict the deformation of lattice structures with manufacturing variability has been advanced, which may lead to greater adoption of this promising new technology.</p>

¹ Overview of the scope of PhD thesis is a short description of objectives of PhD thesis's research and summary of main findings and scientific achievements.

8. Significance of the topic and clarity of problem statement

Very good

The thesis outlines the potential applications of energy-absorbing lattice structures quite well. In summary, automotive applications require the inclusion of structures that are capable of absorbing kinetic energy at moderate strain rates while limiting the maximum force and acceleration exerted on the occupants. Such structures are also subject to space and weight requirements, which make open lattice structures an ideal candidate. With improved understanding of how these structures deform, we could design the structure to follow a prescribed force-deformation trajectory for enhanced protection of the vehicle's occupants, payload, and whatever the vehicle collided with. However, prior models of the plastic deformation of metal lattice structures failed to accurately capture this behavior. With the newly developed models, engineers can predict how metal beam lattices would deform despite variabilities in the as-manufactured geometry.

9. Knowledge of existing literature

Very good

The thesis provides a very thorough review of the relevant existing literature. From this, it is clear that many other researchers have been working on this problem for some time, and in particular within the last 15 years. This is likely due to the rapid growth of the additive manufacturing industry. The thesis provides a systematic analysis of the different aspects of the previous modelling approaches and carefully considers the strengths and weaknesses of each approach. In particular, we see that thin struts produced via additive manufacturing behave quite differently than larger bulk structures would predict. The methods that were used to derive mechanical properties of thin struts are flawed, which propagates into mismatched modelled behavior. The models themselves take various approaches to capture the deflection within the structure despite geometric imperfections but show significant room for improvement. In addition, there are gaps with modelling beyond the linear elastic region and within the relevant band of strain rates. Within this thesis, the knowledge gaps are clearly summarized in chapter 3, followed by specific aims, scientific questions, and hypotheses in chapter 4.

10. Choice of methods and technical soundness

Very good

The methods chosen are quite sound. Some of the major shortcoming in previous studies are that they provide either limited or no experimental validation, or that the experimental methods themselves provide limited applicability for interpretation. This thesis focuses heavily on characterization of the as-built structures, which is thought to be the most accurate method for understanding the capabilities of the manufacturing process. These characterizations are used to develop the non-linear models used to predict deformation behavior. Validation is provided through additional compressive plastic deformation testing of lattice structures at low-to-moderate strain rates that are relevant to the intended automotive application.

11. Quality, originality and significance of the results

Very good

The results provided through this thesis (and analysis thereof) are of very good quality. The papers provide excellent documentation of the methods that were used to achieve these results and thorough discussions of their reliability. Alternative models and explanations are provided as necessary to account for unexpected behavior. Limitations and weaknesses of the employed approach are clearly stated. Results are validated using uncertainty margins, alternative models, and through experiments. As such,



the results are thought to be reliable and can serve as a benchmark for future research. The results showed significant improvements in predictability of structural deflection behavior in thin beam lattices, which represents a meaningful advancement in this field.

12. Quality of attached papers

Very good

The papers are well-written and include clear documentation of the employed methods. All figures and results are clearly presented. Most results include uncertainty analysis or comparison with reference models. The discussions are thorough and account for the observed behavior, with alternative explanations provided when necessary. Comparisons with existing literature are provided. The limitations of the individual studies are considered. The conclusions are clearly stated and are supported by the data and analysis of the paper. The grammar and sentence structure, as well as the overall paper structure, are clear and easy to follow. On average, the papers are being cited more frequently than the journals' Impact Factors or CiteScores would suggest. The overall structure of the cumulative thesis is good and tells a coherent story through the course of this research. As such, the thesis provides the reader with much more value than simply reading the three papers separately.

13. Overall assessment, strengths and weaknesses (based upon the above evaluation categories 8–12)

Very good

This thesis represents a significant contribution to the state of the art in this field of research. The problem statement and motivations for conducting this research is clear. The underlying problems and background research are well-understood and clearly laid out. The combination of experimental and model-based methods gives a sense of increased soundness and applicability of the achieved results. The results show significant improvements in the ability to predict plastic deformation behavior in beam lattices under low-to-moderate strain rates, which is highly relevant to the problem at hand. The quality of the attached papers is high, which hopefully translates to a lasting and widespread impact of this research.

14. Questions and comments

Mr. Červinek did great work in this thesis. I have many technical questions for him regarding the methods and results, which I plan to ask him at the defense.

15. Conclusion

PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the research area and demonstrates the candidate's ability to conduct independent research.

YES

16. Date and signature

Date: 20.02.2023



INSTITUTE OF MACHINE
AND INDUSTRIAL DESIGN



Faculty of Mechanical Engineering
Brno University of Technology

Please note

- A. Evaluate categories 7 to 13 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent. The qualification of 'excellent' should only be given for a PhD Thesis in the top 3% of the research in your field of expertise.
- B. E-mail the completed form to: Klara.Javorcekova@vut.cz

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Ing. Ondřej Červinek / Ondrej.Cervinek@vut.cz
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6. Reviewer
Univ.-Prof. Dipl.-Ing. Dr.techn. Franz Haas/ franz.haas@tugraz.at
TU Graz
7. Overview of the scope of PhD thesis¹
Good
The dissertation deals with a highly relevant topic in the field of mobility and, more generally, product development. Component volumes with lattice structures for damping and energy absorption are not only important for crash boxes in vehicle engineering. The work shows very well the link between materials science, measurement technology and finite element simulation. The results are very convincing. For a complete evaluation, the work misses references to the economic performance of the Additive Manufacturing processes for the production of lattice structures. Production times and references to alternative methods would additionally enrich the work.
8. Significance of the topic and clarity of problem statement
Very good
The priorities of the work are quite clearly defined on the basis of the research questions. The major challenges lie in managing the imperfections of the fabricated lattice structures and the non-linearities of the FE analysis. The dealing with the imperfections in the lattice bars, however, also requires a detailed

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investigation of the measurement technique. This aspect is not sufficiently taken into account in the work. The implementation and presentation of the research questions in working hypotheses is very convincing.

9. Knowledge of existing literature

Very good

The state-of-the-art is very well described and explained in the work. The ideal and real stress-strain behaviour is given as well as a detailed description of the development and application of FEM-approaches for the calculation of lattice structures. One problem area in meshing is certainly the modelling of connection nodes. Further chapters deal with material modelling and the performance of lattice structures in existing and future component applications. In summary, the author has successfully written an excellent presentation of the existing knowledge and at the same time identified gaps in research.

10. Choice of methods and technical soundness

Very good

The competence of the methods and their correct application can be rated as very good. The author of the doctoral thesis succeeded in applying a healthy mixture of experimental and analytical methods. The Design of experiments approach (DOI) was taken into consideration. Also, it was not the claim of the thesis to cover everything and anything. The scientific paper represents a very successful trial to introduce a procedural model for the calculation of lattice structures. Essential information on computing time, scalability and broad application remain open in the dissertation.

11. Quality, originality and significance of the results

Good

Contrary to the evaluation criteria existing literature, methodology and paper quality, the novelty of the dissertation is only limited to special points. The existing literature overview shows that there are some available results in the research field. In addition, it is not obvious, where the independent and new work of Mr. Červinek starts in comparison to the projects before.

12. Quality of attached papers

Very good

The scientific publications cover all the main areas in addressing the research questions. Paper 1 focuses on the test procedures. Paper 2 deals with computational methods. Paper 3 introduces various structural forms in the FE and evaluates energy absorption (stress-strain-response). This publication is clearly the best overview of the work and also deals with deviations in geometry due to the manufacturing process. A clear differentiation of the topics within the three publications is not obvious. The review process of the scientific papers guarantees the novelty of the approaches and confirms the relevance of the topic in the professional world.

13. Overall assessment, strengths and weaknesses (based upon the above evaluation categories 8–12)

Very good

See above.



Faculty of Mechanical Engineering
Brno University of Technology

14. Questions and comments

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15. Conclusion

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YES

16. Date and signature

03/03/2023

Please note

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- B. E-mail the completed form to: Klara.Javorcekkova@vut.cz

Principal supervisor's final report on the PhD study

1. PhD candidate
Ondřej Červinek / ondrej.cervinek@vut.cz
2. Name of PhD programme
Machines and Equipment
3. Title of PhD thesis
Computational models for non-linear mechanical loading analyses of lattice structures made by laser powder bed fusion
4. Principal supervisor
Assoc. prof. Ing. Daniel Koutný, Ph.D. / Daniel.Koutny@vut.cz
5. Co-supervisor
Assoc. prof. Ing. David Paloušek, Ph.D. / palousek@fme.vutbr.cz
6. Stays at other institutions (min. 7 days)
Institute of Lightweight Design and Structural Biomechanics TU Wien / Austria / 01/08/2019 / 09/08/2019 Institute of Lightweight Design and Structural Biomechanics TU Wien / Austria / 01/06/2021 / 31/08/2021 Institute of Virtual Manufacturing ETH Zürich / Switzerland / 04/02/2022 / 31/07/2022
7. Teaching activities
Machine design fundamentals / 182 hrs Machine Design / 78 hrs CAD / 26 hrs Design and CAD / 78 hrs 3D Digital Technology and CAD / 8 hrs Finite Element Method – Structural Analyses / 12 hrs Team Project / 26 hrs Finite Element Method – Advanced Analyses / 8 hrs Analytical Project / 26 hrs Additive Technologies / 100 hrs
8. List of main publications
Papers published in journals with impact factor: VRÁNA, R.; ČERVINEK, O.; MAŇAS, P.; KOUTNÝ, D.; PALOUŠEK, D. Dynamic Loading of Lattice Structure Made by Selective Laser Melting-Numerical Model with Substitution of Geometrical Imperfections, 2018, vol. 11, no. 11, p. 1-22. ISSN 1996-1944 <i>Journal impact factor = 3.748, Quartile Q2, Citations = 18</i>

ČERVINEK, O.; WERNER, B.; KOUTNÝ, D.; VAVERKA, O.; PANTĚLEJEV, L.; PALOUŠEK, D. Computational Approaches of Quasi-Static Compression Loading of SS316L Lattice Structures Made by Selective Laser Melting. *Materials*, 2021, vol. 14, no. 9, p. 1-24. ISSN: 1996-1944.
Journal impact factor = 3.748, Quartile Q2, Citations = 9

WERNER, B.; ČERVINEK, O.; KOUTNÝ, D.; REISINGER, A.; PETTERMANN, H.E.; TODT, M. Numerical and experimental study on the collapse of a triangular cell under. *International Journal of Solids and Structures*, 2021, vol. 236, no. 76, p. 1-12. ISSN: 0020-7683.
Journal impact factor = 3.9, Quartile Q1, Citations = 1

ČERVINEK, O.; PETTERMANN, H.; TODT, M.; KOUTNÝ, D.; VAVERKA, O. Nonlinear dynamic finite element analysis of micro-strut lattice structures made by laser powder bed fusion. *Journal of Materials Research and Technology*, 2022, vol. 18, no. 1-16, p. 3684-3699. ISSN: 2238-7854.
Journal impact factor = 6.267, Quartile Q1, Citations = 1

VRÁNA, R.; KOUTECKÝ, T.; ČERVINEK, O.; ZIKMUND, T.; PANTĚLEJEV, L.; KAISER, J.; KOUTNÝ, D. Deviations of the SLM produced Lattice Structures and Their Influence on Mechanical properties. *Materials*, 2022, vol. 15, no. 9, p. 1-20. ISSN: 1996-1944.
Journal impact factor = 3.748, Quartile Q2, Citations = 2

Papers in conference proceedings:

ČERVINEK, O, R VRÁNA, D KOUTNÝ a D PALOUŠEK. Static and dynamic compression performance of lattice structures made by selective laser melting. In: *European Powder Metallurgy Congress and Exhibition, Euro PM 2019*. EPMA, 2019. ISBN 9781899072514.

VRÁNA, R, O VAVERKA, O ČERVINEK, L PANTĚLEJEV, J HURNÍK, D KOUTNÝ and D PALOUŠEK. Heat treatment of the SLM processed lattice structure made of AISi10Mg and its effect on the impact energy absorption. In: *European Powder Metallurgy Congress and Exhibition, Euro PM 2019*. EPMA, 2019. ISBN 9781899072514.

9. Assessment of the supervision process

Very good

Justification for evaluation: The main communication with the doctoral student regarding the topic of his thesis was carried out in the form of regular meetings on weekly bases. For each meeting, the student prepared summarization of his progress. After his presentation, the choking nodes and the most important point were discussed in detail. Based on the discussion, possible solutions to particular issues were concluded. It is necessary to mention that the student usually reflected the recommendations of his supervisor and was able to proceed to further steps of thesis solution. On the other hand, the student came up with his own innovative ways of solutions which offered new unexplored possibilities. The supervision of the student was without any issues, as he was well organized, punctual, and fulfilled his tasks reliably.

10. Assessment of the candidate's ability to work independently

Excellent

Justification for evaluation: The doctoral student proved his ability to work independently. From the beginning of the studies, he participated on several research projects and contracts with industrial partners. The tasks he received were done on time and in a good quality. He fulfilled his teaching duties with passion, showing a positive feedback from teaching coordinators and students. He proved to be capable to guide student projects, bachelor and diploma thesis. His students passed very well. The student also demonstrated the ability to formulate hypotheses on his own research and test them with experiments he

designed. On the basis of the experiments, he formulated conclusions with suggestions of possible explanations. During his studies, he applied several times for an internship abroad. On the basis of the results achieved on workplaces abroad, he prepared manuscripts of studies which were later published. At the ILSB TU Wien he started long-term cooperation, which led to successful project application focused on international mobility.

11. Assessment of the contribution that the research makes to knowledge in the field

Very good

Justification for evaluation: The doctoral student focused on development and investigation of a nonlinear numerical model of lattice structure loading. The research involved computational models that included unique combination of the most significant geometrical imperfections, specific properties of multi-strut samples, and dynamic effects. These effects have already investigated before, but always separately without consideration of their mutual effects. The combination of effects in computations allowed to achieve an accurate estimation of deformation properties of lattice structures and explore their potential in practical applications. Verified computational models can be used to find efficient structure configurations determined for a specific amount of energy absorbed without prior manufacturing and testing. Using this approach, a variety of energy absorbers with desired deformation characteristics can be designed in the future for the transport industry. Simulations will help to reduce development expenses, shorten development time, and increase efficiency particular designs.

12. Other comments

Conferences and seminars
 11/2020 ANSYS Workbench Mechanical – Nonlinear course
 7/2020 An ECCOMAS Advanced Course on Computational Structural Dynamics 2020
 9/2018 Course of the scientific work basics (AV ČR)
 11/2018 ANSYS Workbench Explicit STR course
 Honours and awards
 01/07/2018 2nd place in Student competition SVS FEM of the best ANSYS project (Prof. Jaroslav Buchar Award) – SVS FEM s.r.o.
 01/06/2018 Winner of Diploma theses conference – BUT FME
 24/11/2020 Rector's Commemorative Medal of Merit – BUT

13. Conclusion

PhD thesis is an independent scientific work that presents a novel solution to a significant problem in the **research area and demonstrates the candidate's ability to conduct independent research.**

YES

14. Date and signature

27/02/2023

Please note

- A. Evaluate categories 9 to 11 using the following scale: unacceptable, acceptable, satisfactory, good, very good, excellent.
- B. In each category 9 to 11 explain reasons for evaluation using between 100–200 words.
- C. E-mail the completed form to: Klara.Javorcekova@vut.cz