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Composites and Lattice Structured Materials as Innovations of Courses in Study Programs of Mechanical Engineering

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ABSTRACT

An ordinary mechanical engineering graduate of the bachelor and master level of university studies has a knowledge focusing mainly on computer support, CAX technologies, manufacturing technologies, smart technologies, production management, and last not least the traditional monolithic technical materials. One of the features that would distinguish that student in the labour market is knowledge of non-standard construction materials, and their applications to the design of e.g. machines to solve engineering problems such as stiffness, lightweight, thermal conduction, and damping of structures. In addition, this knowledge provides the "added value" of the graduate and also makes the study program more attractive. The analysis clearly calls for the need to incorporate the topics of composites and lattice structured materials into the curriculum of existing courses or to create a new course in mechanical engineering study programs. The paper provides and describes the base points for the curriculum of course/s resulting from our own experiences and skills focusing on advanced materials such as composites and lattice structured materials.

Keywords: Curriculum, Modern, Advanced Material, Perspective, Base Knowledge

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1. Introduction

A contradiction has arisen in the last 15 years at faculties of mechanical engineering in Slovakia between the trends to simplification of the mechanics' curriculum due to its difficulty for students, while in praxis the boom in non-standard materials requires a strong foundation of knowledge for standard materials to be a good starting point for the mechanics of various non-standard materials. The trends in the last 15 years and the present state are the following:

Courses focused on technical materials discuss mainly standard traditional monolithic technical materials, and their static properties such as Young's modulus of elasticity, the relationship between statically acting force - deformation, hardness, yield stress, creep, etc. Their dynamic properties are not mentioned or only marginally. Some measurements involved in the educational process are mainly focused on static mechanical properties and standard technical materials. However, the last decades represent a boom in developing new materials with unique chemical composition, thermal-chemical processing, surface treatments, interfaces, internal arrangement, etc. and unique energy absorption dynamic properties.

The base course Technical Materials is the first contact for a university student with the topic of technical materials. The mentioned course in the bachelor's study is focused on the basic physical properties of mainly basic homogeneous structural materials in engineering such as steel, cast iron, aluminium alloys and other metals. The course also deals with other materials such as polymers and composites, but the content is more focused on the classification, physical properties, their production and basic general usage.

Other course involving materials partially is the Parts of Machines course that is focused on the function of the most common components of machines and their basic dimensioning and strength control, and the individual procedures of control calculations are mainly applicable to steels.

Furthermore, the courses focused on the mechanics of deformable bodies (Elasticity and Strength, i.e. Mechanics of Materials) are focused only on a simple basic overview of the problems of basic loadings and stress and deformation analytical calculations as there was a trend to maximally shorten the teaching time of this subject in last 15 years due to its difficulty. Thus, the teaching time was reduced by 69%. i.e. 52 teaching hours of lectures and 52 teaching hours of exercises in just one semester. The students get just simple basics of the designing approach.

In higher grades, i.e. in the second stage of university studies, students have the opportunity to encounter advanced materials in New materials and Progressive materials courses which similarly are not for each student of grade. Moreover, the courses provide the basic classification, physical properties, production technology, and basic general use.

The above-mentioned discrepancy between the descending teaching hours of mechanics and the development of new materials creates a gap that is needful to fill with the new course/s focused on non-standard construction (advanced) materials, including their simulation and the design of structures made from such materials, and the experimental measurement of the mechanical properties. In general, non-standard construction materials, we understand composite materials (fibrous and particulate), mainly with polymer matrix, porous materials with open and closed pores, lattice structured materials, structured composites and materials with internal architecture. In this article, we focus on composite and lattice structured materials as new materials in courses in mechanical engineering.

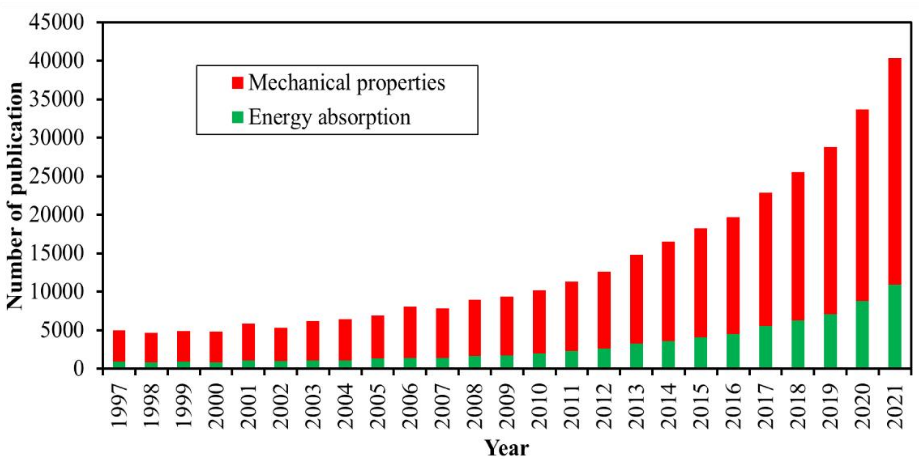


Figure 1. Publications of lattice structures on mechanical properties and energy absorption based on the Elsevier database
Source: (Yin et al., 2023)

The study and research field of composites and lattice structured materials is very large to be able to involve it in deep in study programs of general mechanical engineering. However, the engineers and designers have to have basic knowledge about mainly mechanical properties and their determination and evaluation, moreover, about the basic approaches for designing and solving problems associated with composites and lattice structured materials as advanced materials that will find more applications in future mechanical engineering fields. Many publications (Figure 1) reflected that research and development in the field of composites and lattice structure is very intensive and huge. The motivation to use composite and lattice structure materials is their outstanding properties that are unable to be achieved by homogeneous and monolithic standard materials. The present state of the composites and lattice structures field, mainly in energy absorption properties, is provided in (Yin et al., 2023).

The courses at some prestigious universities incorporate mostly topics of composites and lattice structured materials in individual courses: Mechanics of Composite Structures, University of Maryland (*https://aero.umd.edu/sites/aero.umd.edu/files/syllabi/enae-425-abet-syllabus.pdf*), Composites Engineering Design and Mechanics, University of Southampton (*https://www.southampton.ac.uk/courses/modules/sesg6039*), Mechanics of Composites, University of Illinois (*https://ws.engr.illinois.edu/courses/getfile.asp?id=766*), Cellar Solids: Structure, Properties and Applications, Massachusetts Institute of Technology (*https://ocw.mit.edu/courses/3-054-cellular-solids-structure-properties-and-applications-spring-2015/pages/syllabus/*), Advanced Lightweight and Composite Structures, Cranfield University (*https://www.cranfield.ac.uk/courses/taught/advanced-lightweight-and-composite-structures*), Structure of Materials, École Polytechnique Fédérale de Lausanne (*https://edu.epfl.ch/coursebook/en/structure-of-materials-MSE-238*), etc. The above-mentioned courses are involved mostly in bachelor, master and also postgraduate level of engineering programs, Aerospace Engineering, Materials Science and Engineering study programs.

The facts presented in the Introduction section clearly call for the need to incorporate the topics of composites and lattice structured materials into the curriculum of existing courses or to create a new course in Mechanical Engineering study program. In following part, the paper discusses the essential base curriculum points to innovate the courses in study programs of mechanical engineering. The presented base points resulting from our own experiences and skills regarding topic of composites and lattice structured materials.

2. Base Curriculum Points for Composites and Lattice Structured Materials Courses in the General Mechanical Engineering Study Programs

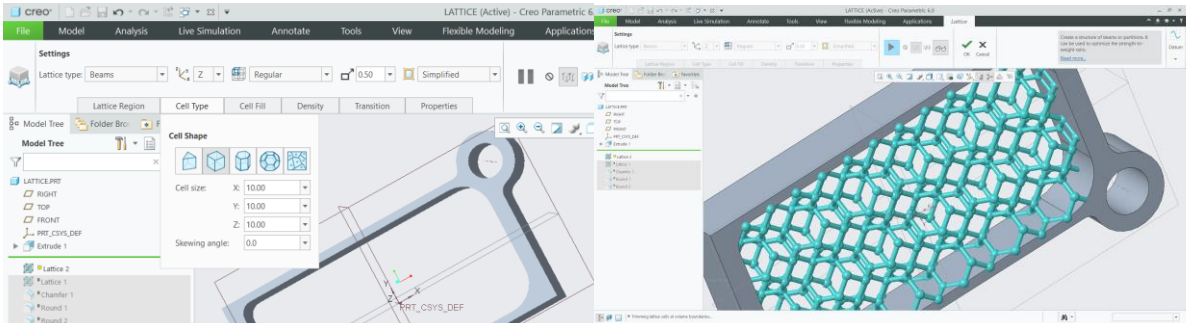
According to Jia et al., 2020, since many composite and lattice structured materials have complex 3D geometries, they pose significant challenges to traditional CAD modelling techniques, numerical simulation, fabrication, experimental measurements, determination of mechanical properties etc. Moreover, these materials have even unusual properties and great potential for designing and tailoring. While significant progress has been made in lattice metamaterial design and fabrication, the realistic application still requires integrated design–modelling–experiment–optimization–manufacturing approaches, spanning material science, applied mechanics, computer science, and mechanical engineering (Jia et al., 2020).

Thus, the courses in mechanics and design of the structures are to be enriched by the following points. Moreover, the following points create the base for the curriculum of a new subject/s Composites and Lattice structured materials – properties and design. Composites are classified as fibre, particular and structured ones. The lattice materials are 2D (general, auxetic, hierarchical) and 3D (truss-based, plate-based, shell-based, hierarchical). However, the composites and lattice structured materials can be combined to create so-called composite lattice structures. Composites and lattice structured materials provide a large area for research and development in future periods.

The literature Yin et al., 2023 introduces the review and states that researchers mainly studied deformation behaviour, the quasi-static and dynamic impact behaviour under in-plane or out-of-plane loading of the hexagonal honeycomb structure, non-hexagonal honeycomb, auxetic and hierarchical 2D and 3D lattice structures in field theory, simulation and experiment in the last 20 years. Moreover, composite materials in the last 20 years have made progress and even one of the trends is to combine the excellent properties of both for various applications.

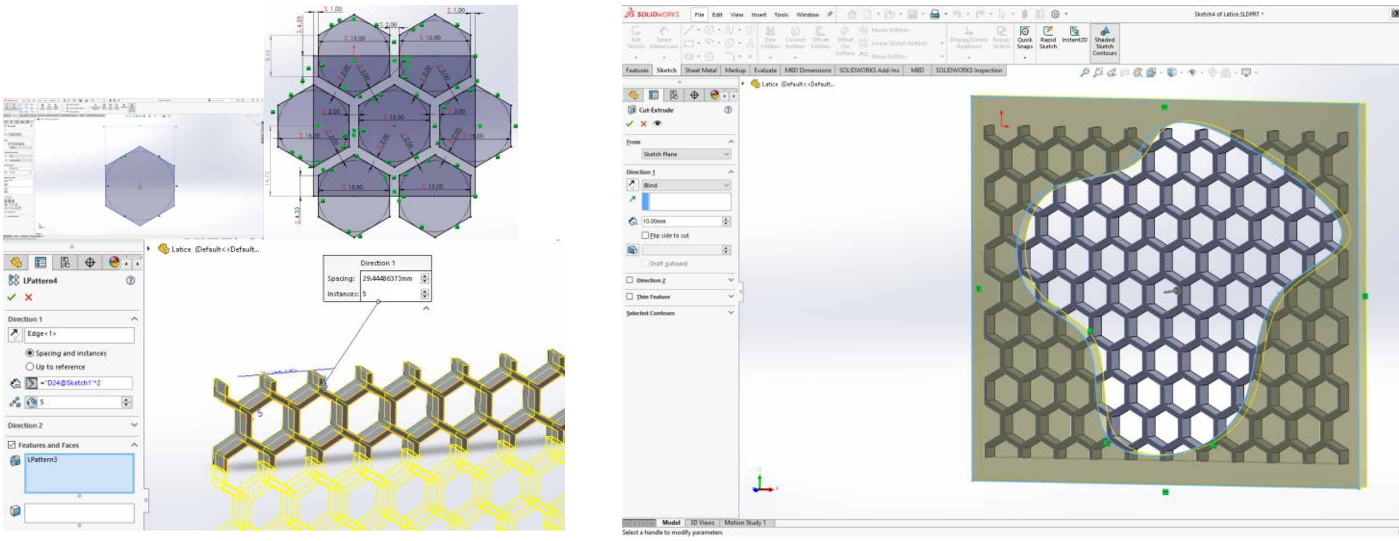
2.1. CAD Software and Lattice Structures Modelling Techniques

CAD systems (e.g. PTC Creo Parametric, Altair) in their upgraded present versions include technology allowing to create and adapt the lattice structures as repeating unit cells mainly in forms shown in Figure 2a such as triangular, hexagonal (Figure 2b), and square profiles. However, the surface or volume can be filled by a lattice of nearly any shape and distribution, even the custom-specific shape of the lattice can be used, in distributed stochastic or formula-driven ways.



(a) (b)

Figure 2. Function Lattice in PTC Creo Parametric (a) options to model 2D, 2.5D and 3D lattice structure and (b) generated 3D lattice structure



(a) (b)

Figure 3. Solid Works (a) model of the cell and patterning (b)creating the final irregular shape with lattice
Source: (Andriichuk, 2021)

Figure 2 shows the PTC Creo Parametric environment with function Lattice and its usage. Software Solid Works (Figure 3) does not involve such a function, the creation of a lattice structure without the specific function is more difficult with more steps and is not quick.

In the above-mentioned CADs, the CAD software user can iterate on the design, adjusting cell types, materials, whatever, until the goal is met. However, meeting a goal can be time-consuming using the standard CAD/CAE software and there is no warranty that the goal was met appropriately. Lattice generation is possible to develop in specific software intended for lattice structures as software nTopology. The mentioned software started in 2015 and it is a unique combination of generative, manual, and simulation-based design tools that help to create lightweight and optimized parts with their functional requirements (more in (https://www.3dnatives.com/en/3d-printing-directory/ntopology/#!).

2.2. New Design Approach - Generative Design and Topology Optimization

The possibility of using and producing composite and lattice structured materials completely changes the approach to designing. Considering the use of 3D printing, we do not need to consider the use of standardized steel semi-products and therefore the design of the shape is adapted only to the function according to the specified requirements. The traditional design process begins with a model based on an engineer's knowledge, however, the generative design begins with design parameters and uses artificial intelligence (AI) to generate the model. Generative design is a CAD engineering software function in which a designer collaborates with AI algorithms to generate and evaluate hundreds of potential designs for a product idea. The generative design process starts with defining the goals and constraints of the project. These include, but are not limited to, design parameters such as product size or geometric dimensions, allowable loads and operating conditions, target weight, materials, manufacturing methods, and cost per unit (https://www.sw.siemens.com/en-US/technology/generative-design/). An example of a generative design with topology optimization is shown in Figure 4.

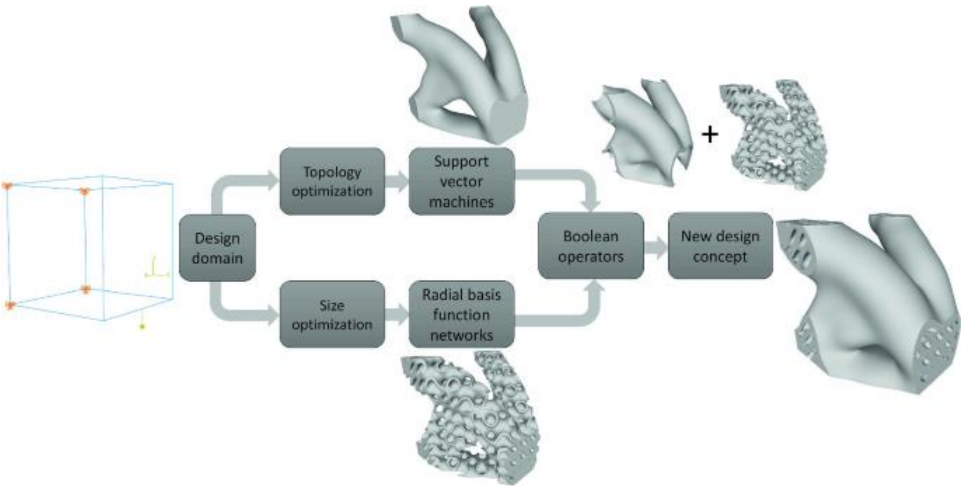


Figure 4. Generative Design and Topology optimisation
Source: (Karlsson. 2021)

2.3. Numerical Simulation – Finite Element Method (FEM) and other Numerical Methods

Numerical simulation tools are part of traditional as well as generative design including topology optimization. The composite and lattice structured materials can be adapted to enhance their performance. The virtual testing of the parameters and properties of cells and entire components can be done by standard FEM software, in advance within the same design environment as the modelling was made (Figure 5).

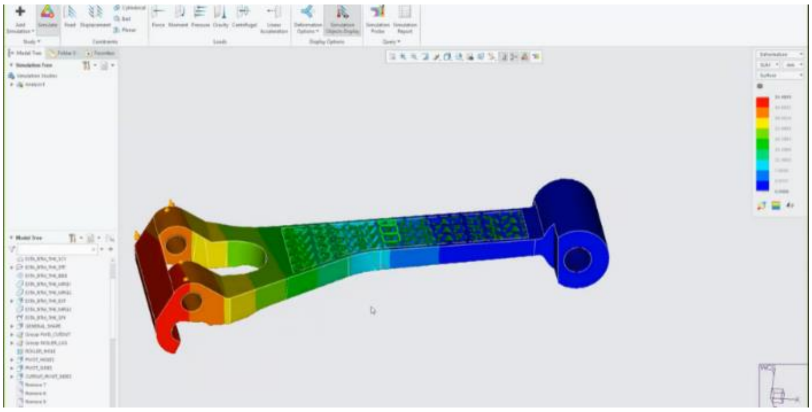


Figure 5. Result window of the component with lattice structure in PTC Creo Simulate
Source: (https://www.ptc.com/en/blogs/cad/lattice-structures-additive-manufacturing)

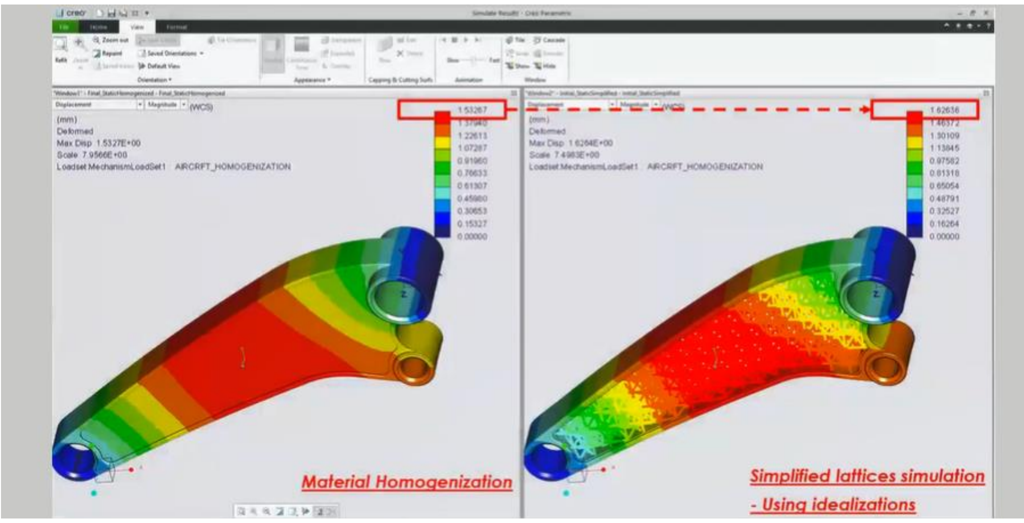
Commercial computational software provides mainly FEA packages, however, computational software such as Altair SimSolid, and PTC Creo Simulation Live based on other non-standard numerical methods are also available. The last mentioned software uses unconventional finite elements, called macroelements or points, respectively. The software is introduced as software without the need for meshing to run structural, thermal, or modal analysis within a very short time, i.e. in seconds.

2.3.1 Micromechanics and Homogeneous vs. Heterogeneous Materials

The first micromechanical models were quite simple representations of the heterogeneous media and their treatment was almost always analytical. Contemporary models are appropriate for the emerging needs of a completely different technology from the polycrystal structures of the metals to the porous stones and the building materials and from the shape memory alloys to the bonds, the tissues, and the composites reinforced by carbon- and glass-fibers (Charalambakis, 2010). Mathematical homogenization techniques provide a rigorous description of homogenization processes and the effective equations for many heterogeneous media. They are not restricted to periodic material structures, uniform stress or strain, or periodic boundary conditions or linear constitutive (Charalambakis, 2010).

Compared to heterogeneous materials, the definition of material properties of homogeneous materials is simple and trivial. The simulation approaches are shown in Figure 6. The model in Figure 6a is geometrically simpler but must include the process of determining homogenized mechanical properties in individual directions of coordinate axes. The geometry of the model in Figure 6b is more complex, but the material properties can be easily defined as it is for homogeneous materials.

Homogenization creates an independent area in the mechanics of advanced materials. The well-known Rule of Mixture is a simple method based on the proportions of individual phases in composite materials, but the topology of the reinforcing elements. i.e. fibres, and particles, affect the properties of the entire material, and the rule of mixture does not take into account the internal topology. It is its disadvantage. Various homogenization methods have been developed using computational mechanics. However, homogenization approaches are not trivial.



(a) (b)

Figure 6. Models of components with lattice structure (a) homogenized (b) non-homogenized models
Source: (https://www.ptc.com/en/blogs/cad/lattice-structures-additive-manufacturing)

2.4. Experimental Determination of Material Damping – Experiment in Laboratory

The experimental determination of mechanical properties needed for simulation input is a serious task.

Composites and lattice structures are well-known for their ability to absorb impact and vibration energy. Therefore, the determination of their damping through, e.g., the logarithmic decrement is needful, as the analytical methods are poor, and/or numerical methods work with models of material damping that can be involved in numerical analysis software, or the damping of structure (also involving some portion of material damping) is set by software user estimation.

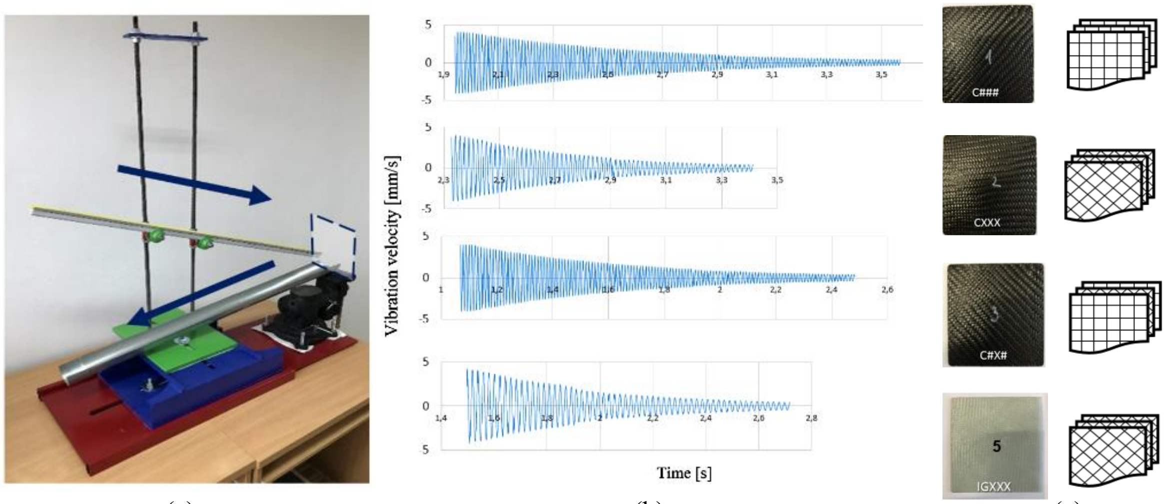
The presented curriculum should involve the use of a developed measuring stand to determine the damping of composite and lattice structured materials. The determination of material damping for dynamic numerical simulation is important as composite and lattice structured materials are known for their very good damping. In the case of traditional designing materials, the damping determination is not important as commonly used standard material steel has poor damping properties.

We developed the measuring stand (Figure 7a) for laboratory determination of material damping. A ball impacts the sample (Figure 7d), and a time record (Figure 7b) is obtained. The tested three-layered laminate samples and their configurations are in Figure 7c.

The damped free vibrations are quasi-periodic because the amplitude of the previous cycle is not the same as the subsequent one. The logarithmic decrement, δ, is determined in the time domain, e.g. the exponential decaying response (Figure 7b) of the free vibrations excited by the ball that generates impulse force. The logarithmic decrement is calculated over several cycles, n:

$$\delta = \frac{1}{n} \ln\left(\frac{X_i}{X_{i+n}}\right), \tag{1}$$

Where X_i and X_{i+n} Are the *i*-th and (*i*+*n*)-th amplitudes of the *i*-th and (*i*+*n*)-th, respectively. Figure 7b provides time-decaying curves for the carbon- (C) and glass-fibre (IG) laminate samples and their lay-up (configurations). The larger the logarithmic decrement is, the less the number of cycles required to reduce the amplitude. Comparing samples CXXX and IGXXX, the logarithmic decrement is 0.0358; and 0.0441 and cycles to reduce the amplitude up to 10% of the maximum are 67; and 59, respectively.



(a) (b) (c)

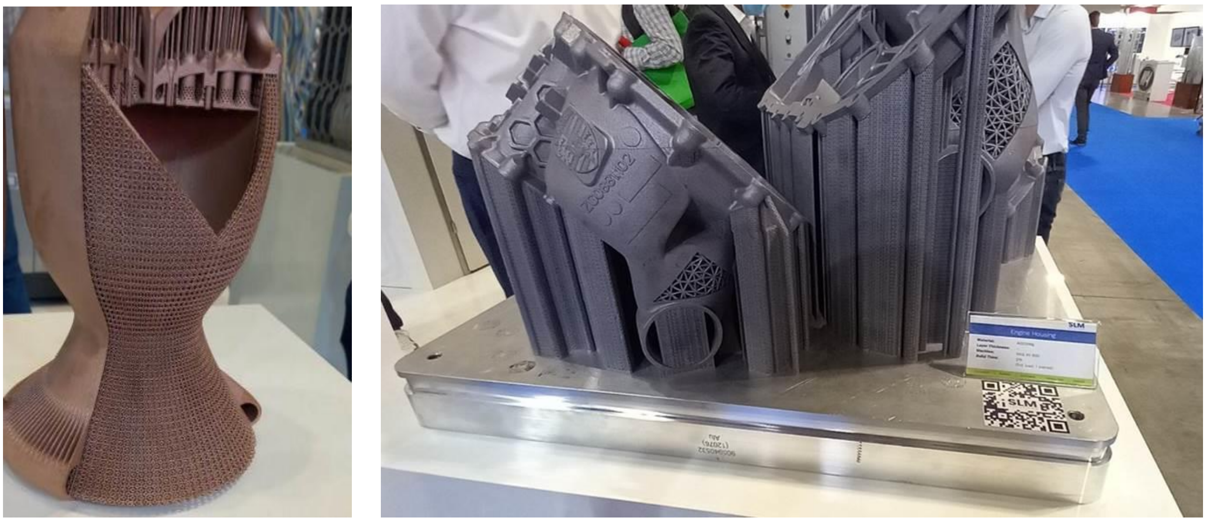
(d)

Figure 7. Experimental determination of material damping in the laboratory (a) measurement stand with a sample in the fixture, (b) Time records of four samples, (c) photo and schema of three-layered samples with specific configuration (# - parallel to the edges of the sample; X - diagonal fibre orientation (45°))
Source: (Murčinková et al., 2019, Murčinková et al., 2020)

2.5. Manufacturing Technologies and Additive Manufacturing of Composites and Lattice structured Materials

In mechanical engineering, it is possible to use appropriate manufacturing processes according to the characteristics of the composite and lattice structured materials. In addition, new progressive manufacturing technologies and cutting tools intended for advanced materials are also being developed.

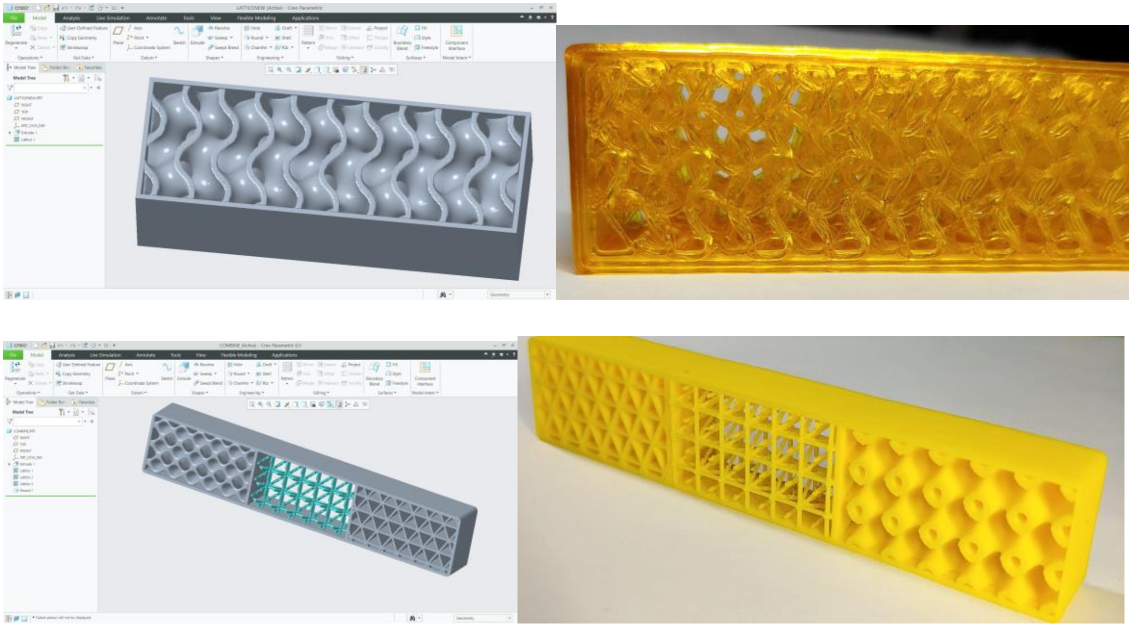
Additive manufacturing, more commonly known as 3D printing, has been at the forefront of manufacturing research for the past couple of decades (Karakurt & Lin, 2020). 3D printing of composite and lattice structured materials is a serious field as many factors influence the final quality of printing. Some 3D printing technologies are well-developed, and some of them are under development. The widely used 3D printing technologies, according to Park et al., 2022, are material extrusions, such as filament fused fabrication and direct ink writing; vat photo-polymerization (or stereolithography), material jetting, binder jetting, and powder bed fusion. The complex geometry components are possible to manufacture with advanced 3D printing as visible in Figure 8. Moreover, the 4D printing concept has experienced rapid development over the past years and has attracted significant attention from engineers and scientists (Alshahrani, 2021).



(a) (b)

Figure 8. Printed lattice structures, (a) Thrust chamber and (b) engine housing
Source: photos made by the first author at EMO Milano, 4-9 October, 2021

Figure 9 shows the CAD models with lattice structures in PTC Creo Parametric and printed samples by a student of Master science thesis in Andriichuk, 2021, with the supervision of the first author of this paper.



(a) (b)

Figure 9. (a) CAD models in PTC Creo Parametric and (b) samples printed by filament fused fabrication
Source: (Andriichuk, 2021)

Manufacturing Methodologies of glass and carbon fibre-reinforced polymer (GFRP and CFRP) composites (according to Rajak et al., 2021) are the following

- Matched Die Molding - Injection Molding, Silicone Rubber Mold Process, Compression Molding Process, Resin Transfer Molding Process, Vacuum-Assisted Resin Transfer Molding Process,
- Contact Molding: Dry Hand Lay-Up Process, Spray Lay-Up Process, Filament Winding Process, Pultrusion Process, Autoclave Molding Process,

One can see that composite and lattice structured materials open a wide range of production technologies with individual parameters to set and problems to solve within them.

3. Conclusions and Outcomes

The paper provides and describes the base points for the new curriculum of course/s focusing on advanced materials such as composites and lattice structured materials. Expanding the scope of student knowledge base will have several significant outcomes on students, study quality and practical applications.

Outcomes for students: (a) broader knowledge base – the graduates without knowledge and designing skills in composite and lattice structured materials are the "old-fashioned" graduates; the faculties and universities have to provide a curriculum in this field to be modern, moreover, mechanics has to regain its signified and irreplaceable place among other bachelor and engineering courses, as mechanical engineers are not strong without mechanics; (b) improved career prospects – the graduates will be more competitive in the job market; (c) enhanced problem-solving skills – the complexity of composite behaviour and lattice mechanics will challenge students to think critically and develop more innovative solutions.

Outcomes for the quality of study: (a) interdisciplinary learning - integrating materials science, structural engineering, and manufacturing processes; (b) more engaging teaching methods - the course may include computational modeling, experimental case studies, and industry collaborations, making learning more dynamic and applicable; (c) increased research opportunities – new scopes of thesis topics, projects, (d) need to update the textbooks.

Outcomes for industry: (a) innovation in structural design – the graduates will be able to design lighter, stronger, and more efficient structures using the composite and lattice materials, (b) sustainability and efficiency of structures - understanding advanced materials can lead to more sustainable construction practices, such as reduced material usage and optimized performance (c) industry adaptation - modern materials need the next generation of design as the conventional monolithic materials can be replaced with appropriate parts of machines, machine tools and devices. Perspective and applications of modern materials involving composite and lattice structured materials are beneficial for any industry, for a variety of applications in structural, biomedical, electrochemical energy storage, electronics, and robotics applications as they create high-performance products with multi-scale optimized structure and function. The application domain is distributed in aerospace, transportation, national defense, automotive, medical treatment, construction and sports (Yin et al., 2023).

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