VIŠJA TRDNOST

UČNI NAČRT PREDMETA/COURSE SYLLABUS

Predmet:	Višja trdnost
Course title:	Advanced Strength of Materials
Članica nosilka/UL Member:	UL FS

Študijski programi in stopnja	Študijska smer	Letnik	Semestri	Izbirnost
Strojništvo - Razvojno raziskovalni program, druga stopnja, magistrski	Mehanika (smer)	1. letnik	1. semester	obvezni

Univerzitetna koda predmeta/University course code:	0566892
Koda učne enote na članici/UL Member course code:	6034-M

Predavanja /Lectures	Seminar /Seminar	Vaje /Tutorials	Klinične vaje /Clinical tutorials	Druge oblike študija /Other forms of study	Samostojno delo /Individual student work	ECTS
30		30			65	5

Nosilec predmeta/Lecturer:	izr. prof. dr. Miha Brojan, Jaka Tušek

Izvajalci predavanj:	
Izvajalci seminarjev:	
Izvajalci vaj:	
Izvajalci kliničnih vaj:	
Izvajalci drugih oblik:	
Izvajalci praktičnega usposabljanja:	

Vrsta predmeta/Course type:	Obvezni strokovni predmet na smeri Mehanika, ki je izbirni strokovni predmet na ostalih smereh./Compulsory specialised course in the study of Mechanics, which is an elective specialised course in other fields of study.

Jeziki/Languages:	Predavanja/Lectures:	Slovenščina
	Vaje/Tutorial:	Slovenščina

Pogoji za vključitev v delo oz. za opravljanje študijskih obveznosti:	**Prerequisites:**
Izpolnjevanje pogojev za vpis v Magistrski študijski program II. stopnje Strojništvo - Razvojno raziskovalni program.	Meeting the enrollment conditions for the Master's study programme of Mechanical Engineering - Research and Development program.

Vsebina:	**Content (Syllabus outline):**
1. Vsebina 1. Predavanja - Seznanitev s študijskimi pravili in obveznostmi	1. Topics of Lecture 1: - Definition of rules and obligations for following

- Predstavitev študijske literature - Pregled celotne vsebine predavanj - Kratek uvod v tenzorsko analizo 2. Vsebina 2. Predavanja - Koncept zvezne snovi, nadaljevanje teorije napetosti iz predmeta Trdnost (iz 2D v 3D) - Cauchyeva definicija napetostnega vektorja, definicije z limito: normalne in strižne napetosti, ravnovesja na končnem volumnu deformiranega telesa, Cauchyev stavek 3. Vsebina 3. Predavanja - Napetostni tenzorji (Cauhyjev, prvi Piola-Kirchhoffov, drugi Piola-Kirchhoffov, Biotov,…) - Deviatorični in krogelni del tenzorja napetosti 4. Vsebina 4. Predavanja - Napetostno stanje pri linearni transformaciji koordinatnega sistema, ekstremne normalne in strižne napetosti v prostoru - Glavne invariante napetostnega tenzorja in njegovega deviatoričnega dela 5. Vsebina 5. Predavanja - Rigorozna izpeljava teorije deformacij - Vektor premika, gradient deformacij, tenzorji deformacij, teorija velikih/majhnih deformacij 6. Vsebina 6. Predavanja - Geometrijska interpretacija komponent tenzorja majhnih specifičnih deformacij - Kompatibilnostne enačbe za enostavno in večkrat povezana območja 7. Vsebina 7. Predavanja - Elastična energija obremenjenega telesa (izpeljano iz osnovnih principov Termodinamike) - Energijska metoda, volumska gostota notranje energije, deformacijsko delo 8. Vsebina 8. Predavanja - Princip virtualnega dela - Virtualno delo za nosilec, ki je obremenjen z osno in strižno silo, ter upogibnim momentom 9. Vsebina 9. Predavanja - Idealno elastično gradivo, Greenova elastičnost - Splošna in posebne anizotropije gradiva - Izotropno linearno elastično gradivo (napetost kot funkcija spec. deformacij in inverzno) 10. Vsebina 10. Predavanja - Določitev snovnih konstant iz eksperimentov - Hookeov zakon, razdelitev na deviatorični in krogelni del 11. Vsebina 11. Predavanja - Volumsko in distorzijsko delo - Vpliv temperaturnih obremenitev 12. Vsebina 12. Predavanja - Pregled enačb elastostatike - Navier-Lamejeve enačbe 13. Vsebina 13. Predavanja - Beltrami-Michellove enačbe - Hookeov zakon za posebna napetostno-deformacijska stanja 14. Vsebina 14. Predavanja	and completing the course - Presentation of relevant study literature - Complete overview of course topics - Short introduction to Tensor analysis 2. Topics of Lecture 2: - Concept of a "continuum", expansion of Theory of mechanical stresses from the course "Strength of materials" (2D to 3D) - Cauchy's definition of stress vector, defined with limits: normal and shear stresses, equilibrium of loads on a finite volume in a deformed body, Cauchy's stress theorem 3. Topics of Lecture 3: - Stress tensors (Cauchy, 1st Piola-Kirchhoff, 2nd Piola-Kirchhoff, Biot, …) - Deviatoric and hydrostatic part of stress tensor 4. Topics of Lecture 4: - Transformation rule of stress tensor for a linear transformation of the coordinate system, principal stresses and maximum shear stresses in 3D - Invariants of the stress tensor and invariants of the deviatoric part of the stress tensor 5. Topics of Lecture 5: - Rigorous derivation of Strain theory - Displacement vector, deformation gradient, deformation tensors, small/finite strain theory 6. Topics of Lecture 6: - Geometric interpretation of the components of the small strain tensor - Compatibility conditions for strains in simply and multiply connected regions 7. Topics of Lecture 7: - Elastic strain energy of a body subjected to external loads (derived from fundamental (Thermodynamic) principles) - Energy methods, volume density of internal energy, deformation work/energy 8. Topics of Lecture 8: - Principle of virtual work - Virtual work for a beam subjected to axial force loads, transversal force loads and bending moments 9. Topics of Lecture 9: - Ideally elastic material, Green elasticity - General and specific material anisotropy - Isotropic, linearly elastic material (stress as function of strain and vice versa) 10. Topics of Lecture 10: - Determining material constants from experiments - Hooke's law, separation of deviatoric and hydrostatic parts of stress/strain tensor 11. Topics of Lecture 11: - Volumetric and distortion work/energy - Effect of temperature, temperature load 12. Topics of Lecture 12: - Overview of equations in elastostatics - Navier-Lame equations 13. Topics of Lecture 13: - Beltrami-Michell equations

- Airyeva napetostna funkcija - Primeri uporabe Airyeve napetostne funkcije 15. Vsebina 15. Predavanja - Računalniške simulacije (FEM analize v komercialnih programih) - Kompleksnejši primeri iz prakse	- Hooke's law for special stress-strain states 14. Topics of Lecture 14: - Airy stress functions - Examples of the use of Airy stress functions 15. Topics of Lecture 15: - Computer simulations (FEM analysis in commercially available software) - Complex real-life examples and case studies

Temeljna literatura in viri/Readings:

1. S. Srpčič: Mehanika trdnih teles, FGG, 2003 [COBISS.SI-ID 126565120].
2. M. Stanek, G. Turk: Osnove mehanike trdnih teles, FGG, 2008 [COBISS.SI-ID 237288960].
3. F. Kosel: Višja trdnost, zbirka rešenih nalog, FS, 2009 [COBISS.SI-ID 247680256].
4. B. Štok: Mehanika deformabilnih teles, zbirka rešenih problemov I in II del, FS, 1988 [COBISS.SI-ID 3769600].
5. J.N. Reddy: An Introduction to Continuum Mechanics, Cambridge University Press, 2013 [COBISS.SI-ID 135000579].
6. A. Bower: Applied mechanics of solids, CRC Press, 2010 [COBISS.SI-ID 11886107].

Cilji in kompetence:	**Objectives and competences:**
Cilji: 1. Naučiti se uporabljati zahtevna matematična orodja v mehaniki 2. Naučiti se fizikalno-matematičnega modeliranja deformabilnih teles z zapletenejšimi napetostno-deformacijskimi in reološkimi odzivi 3. Naučiti se dimenzioniranja večkrat statično nedoločenih konstrukcij Kompetence: 1. S1-MAG + P3-MAG: Sposobnost uporabe zahtevnih matematičnih orodij v mehaniki 2. S2-MAG + P4-MAG: Sposobnost fizikalno-matematičnega modeliranja deformabilnih teles z zapletenejšimi napetostno-deformacijskimi in reološkimi odzivi 3. S7-MAG + P1-MAG: Sposobnost dimenzioniranja statično nedoločenih konstrukcijskih elementov	Goals: 1. Learn to use advanced mathematical tool in mechanics 2. Learn to build physical and mathematical models of deformable bodies of complex stress-strain states and rhological responses 3. Learn to design statically multiply indeterminate structures Competences: 1. S1-RRP + P4-RRP: Ability to use advanced mathematical tool in mechanics 2. S6-RRP + P1-RRP: Ability to build physical and mathematical models of deformable bodies of complex stress-strain states and rhological responses 3. S2-RRP: design statically multiply indeterminate structures

Predvideni študijski rezultati:	**Intended learning outcomes:**
Znanja: Z1: Poglobljeno strokovno teoretično in praktično znanje na določenem področju, podprto s širšo teoretično in metodološko osnovo. • Poglobljeno poznavanje napetostnih in deformacijskih stanj v splošnih deformabilnih telesih • Poglobljeno poznavanje mehanizmov porušitve konstrukcijskih elementov	Knowledge: Z1: Thorough professional theoretical and practical knowledge in a selected field of expertise that is supported with a broad theoretical and methodological basis. • In-depth understanding of stress and strain states in general deformable bodies • In-depth understanding of the failure mechanisms in structural elements

• Poglobljeno znanje o matematični zasnovi reoloških modelov Spretnosti: S1.1 Izvajanje kompleksnih operativno-strokovnih opravil, ki vključujejo tudi uporabo metodoloških orodij. • Izračun kompleksnih napetostno-deformacijskih stanj v splošnih deformabilnih telesih • Dimenzioniranje statično nedoločenih konstrukcijskih elementov	• In-depth understanding of mathematical structure of rheological models Skills: S1.1 Executing complex operationa-professional tasks that incorporate usage of methodological tools. • Calcualtions of complex stress-strain states in general deformable bodies • Design of statically indeterminate structural elements

Metode poučevanja in učenja:	**Learning and teaching methods:**
Klasične oblike poučevanja: 1. P1 Avditorna predavanja z reševanjem izbranih - za področje značilnih - teoretičnih in praktično uporabnih primerov. 2. P2 Obravnava snovi po urejeni in vnaprej razloženi sistematiki. 3. P3 Avditorne vaje, kjer se teoretično znanje s predavanj podkrepi z računskimi primeri. 4. P4 Laboratorijske vaje z namenskimi didaktičnimi pripomočki • Eksperimentalna naprava za spremljanje upogibnih deformacij • Trgalni stroj • Eksperimentalna naprava za spremljanje deformacij statično nedoločenega paličja • Eksperiment za prikaz napetosti na osnovi fotoelastičnosti • Eksperimentalna priprava za prikaz tlačno-volumske karakteristike tankih zaprtih lupin 5. P5 Uporaba študijskega gradiva v obliki • E-domače naloge • E-zapiski • Tiskana verzija Moderne in prožne oblike poučevanja: 1. P6 Interaktivna predavanja 2. P7 Študij literature in razprava 3. P9 Skupinsko delo (razprave za – proti, razprave o prebranem) Nekaj primerov uporabe IKT: 1. P12 Individualizirane domače naloge 2. P14 Virtualni eksperimenti (FEM simulacije) 3. P15 Uporaba video vsebin kot priprava na predavanja in vaje	Conventional teaching methods: 1. P1 Auditorial lectures with solving selected field-specific theoretical and applied use cases. 2. P2 Presenting the content according to the explained system. 3. P3 Auditorial exrecises, in which theoretical content from the lectures is supplemented with practical examples. 4. P4 Laboratory exercises with special-purpose didactic devices • Experimental apparatus for the analysis of beam bending • Tensile testing machine • Experimental apparatus for the analysis of statically indeterminate bar structures • Experimental apparatus based on photoelastic effect • Experimental apparatus for the analysis of pressure-volume relation in pressure vessels 5. P5 Application of study material • E-homework • E-manuscripts • Printed versions Contemporary and flexible teaching methods: 1. P6 Interactive lectures 2. P7 Literature study and discussion 3. P9 Team work (discussion pro and contra, discussion of the studied content) Some cases of ICT usage: 1. P12 Individualised homeworkes in a web classroom 2. P14 Virtual experiments (FEM simulations) 3. P15 Application of videos for preparations to the lectures and exercise

Načini ocenjevanja:	Delež/Weight	Assessment:
Izpit (predavanja - teorija)	20,00 %	Examination (lectures - theory)
Izpit (vaje – naloge, prepračuni)	60,00 %	Examination (exercises – design calculations)
Laboratorijske vaje	10,00 %	Laboratory exercises
Domača naloga	10,00 %	Homework

Ocenjevalna lestvica:	Grading system:
5 - 10, pri čemer velja, da je pozitivna ocena od 6 - 10	5 - 10, a student passes the exam if he is graded from 6 to 10

Reference nosilca/Lecturer's references:

Miha Brojan:

1. PORENTA, Luka, LAVRENČIČ, Marko, DUJC, Jaka, **BROJAN, Miha**, TUŠEK, Jaka, BRANK, Boštjan. Modeling large deformations of thin-walled SMA structures by shell finite elements. Communications in Nonlinear Science and Numerical Simulation. okt. 2021, vol. 101, no. 105897, str. 1-29, ilustr. ISSN 1007-5704. https://repozitorij.uni-lj.si/IzpisGradiva.php?id=127201, DOI: 10.1016/j.cnsns.2021.105897. [COBISS.SI-ID 64322307]
2. SARKAR, S., ČEBRON, Matjaž, **BROJAN, Miha**, KOŠMRLJ, Andrej. Method of image charges for describing deformation of bounded two-dimensional solids with circular inclusions. Physical review. E. 2021, vol. 103, iss. 5, str. 1-34, ilustr. ISSN 2470-0053. https://journals.aps.org/pre/abstract/10.1103/PhysRevE.103.053004, DOI: 10.1103/PhysRevE.103.053004. [COBISS.SI-ID 64657923]
3. SARKAR, S., ČEBRON, Matjaž, **BROJAN, Miha**, KOŠMRLJ, Andrej. Elastic multipole method for describing deformation of infinite two-dimensional solids with circular inclusions. Physical review. E. 2021, vol. 103, iss. 5, str. 1-25, ilustr. ISSN 2470-0053. https://journals.aps.org/pre/abstract/10.1103/PhysRevE.103.053003. [COBISS.SI-ID 64663811]
4. VENKATESH, Ragunanth, VOLOSHIN, Arkady S., EMRI, Igor, **BROJAN, Miha**, GOVEKAR, Edvard. Digital image correlation based internal friction characterization in granular materials. Experimental mechanics. Tiskana izd. Apr. 2020, vol. 60, iss. 4, str. 481-492, ilustr. ISSN 0014-4851. https://link.springer.com/article/10.1007%2Fs11340-019-00570-8, DOI: 10.1007/s11340-019-00570-8. [COBISS.SI-ID 17018651]
5. RAHMANI, Ramin, **BROJAN, Miha**, ANTONOV, Maksim, PRASHANTH, Konda Gokuldoss. Perspectives of metal-diamond composites additive manufacturing using SLM-SPS and other techniques for increased wear-impact resistance. International journal of refractory metals & hard materials. [Print ed.]. Apr. 2020, vol. 88, str. 1-13, ilustr. ISSN 0958-0611. https://www.sciencedirect.com/science/article/pii/S0263436819309977, DOI: 10.1016/j.ijrmhm.2020.105192. [COBISS.SI-ID 17015579]

Jaka Tušek:

1. PORENTA, Luka, BRANK, Boštjan, **TUŠEK, Jaka**, BROJAN, Miha. Shell-based finite element model for predicting buckling stability of superelastic structures for elastocaloric cooling. Thin-walled structures. 2025, vol. 208, [art.] 112825, str. 1-15, ilustr. ISSN 1879-3223. https://www.sciencedirect.com/science/article/pii/S0263823124012643, DOI: 10.1016/j.tws.2024.112825. [COBISS.SI-ID 220697347]
2. NEBOT-ANDRÉS, Laura, PETRUZZIELLO, Fabio, APREA, Ciro, LLOPIS, Rodrigo, ŽEROVNIK, Andrej, MAIORINO, Angelo, **TUŠEK, Jaka**. Parametric analysis of hybrid elastocaloric – CO2 cooling system. Applied thermal engineering. Sept. 2024, vol. 253, [article no.] 123843, str. 1-10,

ilustr. ISSN 1359-4311. https://www.sciencedirect.com/science/article/pii/S1359431124015114, DOI: 10.1016/j.applthermaleng.2024.123843. [COBISS.SI-ID 206758147]

3. AHČIN, Žiga, KITANOVSKI, Andrej, **TUŠEK, Jaka**. Latent thermal energy storage using solid-state phase transformation in caloric materials. Cell reports physical science. Sep. 2024, vol. 5, iss. 9, [article no.] 102175, str. 1-18, ilustr. ISSN 2666-3864. https://www.sciencedirect.com/science/article/pii/S2666386424004600, DOI: 10.1016/j.xcrp.2024.102175. [COBISS.SI-ID 206949635]
4. AHČIN, Žiga, **TUŠEK, Jaka**. Parametric analysis of fatigue-resistant elastocaloric regenerators : Tensile vs. compressive loading. Applied thermal engineering. Aug. 2023, vol. 231, str. 1-13, ilustr. ISSN 1359-4311. https://www.sciencedirect.com/science/article/pii/S1359431123010256, DOI: 10.1016/j.applthermaleng.2023.120996. [COBISS.SI-ID 157626371]

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