

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:	Jaka Tušek, Miha Brojan
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Izvajalci predavanj:	
Izvajalci seminarjev:	
Izvajalci vaj:	
Izvajalci kliničnih vaj:	
Izvajalci drugih oblik:	
Izvajalci praktičnega usposabljanja:	

Vrsta predmeta/Course	Obvezni strokovni predmet na smeri Mehanika, ki je
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type:

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
 - 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 (Cauchyjev, 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

1. Topics of Lecture 1:
 - Definition of rules and obligations for following 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

<ul style="list-style-type: none"> - Rigorozna izpeljava teorije deformacij - Vektor premika, gradient deformacij, tenzorji deformacij, teorija velikih/majhnih deformacij <p>6. Vsebina 6. Predavanja</p> <ul style="list-style-type: none"> - Geometrijska interpretacija komponent tenzorja majhnih specifičnih deformacij - Kompatibilnostne enačbe za enostavno in večkrat povezana območja <p>7. Vsebina 7. Predavanja</p> <ul style="list-style-type: none"> - Elastična energija obremenjenega telesa (izpeljano iz osnovnih principov Termodinamike) - Energijska metoda, volumska gostota notranje energije, deformacijsko delo <p>8. Vsebina 8. Predavanja</p> <ul style="list-style-type: none"> - Princip virtualnega dela - Virtualno delo za nosilec, ki je obremenjen z osno in strižno silo, ter upogibnim momentom <p>9. Vsebina 9. Predavanja</p> <ul style="list-style-type: none"> - Idealno elastično gradivo, Greenova elastičnost - Splošna in posebne anizotropije gradiva - Izotropno linearno elastično gradivo (napetost kot funkcija spec. deformacij in inverzno) <p>10. Vsebina 10. Predavanja</p> <ul style="list-style-type: none"> - Določitev snovnih konstant iz eksperimentov - Hookeov zakon, razdelitev na deviatorični in krogelni del <p>11. Vsebina 11. Predavanja</p> <ul style="list-style-type: none"> - Volumsko in distorzijsko delo - Vpliv temperaturnih obremenitev <p>12. Vsebina 12. Predavanja</p> <ul style="list-style-type: none"> - Pregled enačb elastostatike - Navier-Lamejeve enačbe <p>13. Vsebina 13. Predavanja</p> <ul style="list-style-type: none"> - Beltrami-Michellove enačbe - Hookeov zakon za posebna napetostno-deformacijska stanja <p>14. Vsebina 14. Predavanja</p> <ul style="list-style-type: none"> - Airyeva napetostna funkcija - Primeri uporabe Airyeve napetostne funkcije <p>15. Vsebina 15. Predavanja</p> <ul style="list-style-type: none"> - Računalniške simulacije (FEM analize v komercialnih programih) 	<p>5. Topics of Lecture 5:</p> <ul style="list-style-type: none"> - Rigorous derivation of Strain theory - Displacement vector, deformation gradient, deformation tensors, small/finite strain theory <p>6. Topics of Lecture 6:</p> <ul style="list-style-type: none"> - Geometric interpretation of the components of the small strain tensor - Compatibility conditions for strains in simply and multiply connected regions <p>7. Topics of Lecture 7:</p> <ul style="list-style-type: none"> - 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 <p>8. Topics of Lecture 8:</p> <ul style="list-style-type: none"> - Principle of virtual work - Virtual work for a beam subjected to axial force loads, transversal force loads and bending moments <p>9. Topics of Lecture 9:</p> <ul style="list-style-type: none"> - Ideally elastic material, Green elasticity - General and specific material anisotropy - Isotropic, linearly elastic material (stress as function of strain and vice versa) <p>10. Topics of Lecture 10:</p> <ul style="list-style-type: none"> - Determining material constants from experiments - Hooke's law, separation of deviatoric and hydrostatic parts of stress/strain tensor <p>11. Topics of Lecture 11:</p> <ul style="list-style-type: none"> - Volumetric and distortion work/energy - Effect of temperature, temperature load <p>12. Topics of Lecture 12:</p> <ul style="list-style-type: none"> - Overview of equations in elastostatics - Navier-Lame equations <p>13. Topics of Lecture 13:</p> <ul style="list-style-type: none"> - Beltrami-Michell equations - Hooke's law for special stress-strain states <p>14. Topics of Lecture 14:</p> <ul style="list-style-type: none"> - Airy stress functions
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- Kompleksnejši primeri iz prakse	- 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
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Temeljna literatura in viri/Readings:

1. S. Srpcič: 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:

<p>Cilji:</p> <ol style="list-style-type: none"> 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 <p>Kompetence:</p> <ol style="list-style-type: none"> 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 	<p>Goals:</p> <ol style="list-style-type: none"> 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 rheological responses 3. Learn to design statically multiply indeterminate structures <p>Competences:</p> <ol style="list-style-type: none"> 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 rheological responses 3. S2-RRP: design statically multiply indeterminate structures
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Predvideni študijski rezultati:

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
- 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

Intended learning outcomes:

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
- In-depth understanding of mathematical structure of rheological models

Skills:

S1.1 Executing complex operational-professional tasks that incorporate usage of methodological tools.

- Calculations of complex stress-strain states in general deformable bodies
- Design of statically indeterminate structural elements

Metode poučevanja in učenja:

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 namenski didaktičnimi pripomočki
 - Eksperimentalna naprava za spremljanje upogibnih deformacij
 - Trgalni stroj

Learning and teaching methods:

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 exercises, 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

<ul style="list-style-type: none"> • 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 <p>5. P5 Uporaba študijskega gradiva v obliki</p> <ul style="list-style-type: none"> • E-domače naloge • E-zapiski • Tiskana verzija <p>Moderne in prožne oblike poučevanja:</p> <ol style="list-style-type: none"> 1. P6 Interaktivna predavanja 2. P7 Študij literature in razprava 3. P9 Skupinsko delo (razprave za – proti, razprave o prebranem) <p>Nekaj primerov uporabe IKT:</p> <ol style="list-style-type: none"> 1. P12 Individualizirane domače naloge 2. P14 Virtualni eksperimenti (FEM simulacije) 3. P15 Uporaba video vsebin kot priprava na predavanja in vaje 	<p>analysis of statically indeterminate bar structures</p> <ul style="list-style-type: none"> • Experimental apparatus based on photoelastic effect • Experimental apparatus for the analysis of pressure-volume relation in pressure vessels <p>5. P5 Application of study material</p> <ul style="list-style-type: none"> • E-homework • E-manuscripts • Printed versions <p>Contemporary and flexible teaching methods:</p> <ol style="list-style-type: none"> 1. P6 Interactive lectures 2. P7 Literature study and discussion 3. P9 Team work (discussion pro and contra, discussion of the studied content) <p>Some cases of ICT usage:</p> <ol style="list-style-type: none"> 1. P12 Individualised homeworks in a web classroom 2. P14 Virtual experiments (FEM simulations) 3. P15 Application of videos for preparations to the lectures and exercise
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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
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Reference nosilca/Lecturer's references:

Miha Brojan:

1. TUŠEK, Jaka, ŽEROVNIK, Andrej, ČEBRON, Matjaž, **BROJAN, Miha**, ŽUŽEK, Borut, ENGELBRECHT, Kurt, CADELLI, Andrea. Elastocaloric effect vs fatigue

life : exploring the durability limits of Ni-Ti plates under pre-strain conditions for elastocaloric cooling. *Acta materialia*, ISSN 1359-6454. [Print ed.], May 2018, vol. 150, str. 295-307, ilustr.

<https://www.sciencedirect.com/science/article/pii/S135964541830226X>, doi: [10.1016/j.actamat.2018.03.032](https://doi.org/10.1016/j.actamat.2018.03.032). [COBISS.SI-ID [15964187](#)], [JCR, SNIP, WoS do 15. 9. 2019: št. citatov (TC): 9, čistih citatov (CI): 9, Scopus do 29. 9. 2019: št. citatov (TC): 11, čistih citatov (CI): 11]

2. **BROJAN, Miha**, TERWAGNE, Denis, LAGRANGE, Romain, REIS, Pedro. Wrinkling crystallography on spherical surfaces. *Proceedings of the National Academy of Sciences of the United States of America*, ISSN 0027-8424, Jan. 2015, vol. 112, no. 1, str. 14-19, ilustr., doi: [10.1073/pnas.1411559112](https://doi.org/10.1073/pnas.1411559112). [COBISS.SI-ID [13852187](#)], [JCR, SNIP, WoS do 13. 10. 2019: št. citatov (TC): 19, čistih citatov (CI): 18, Scopus do 28. 8. 2019: št. citatov (TC): 19, čistih citatov (CI): 18]
3. BOGATAJ, Matej, KOSEL, Franc, NORRIS, R., KRKOVIČ, Matija, **BROJAN, Miha**. Biomechanical study of different plate configurations for distal humerus osteosynthesis. *Medical & biological engineering & computing : journal of the International Federation for Medical & Biological Engineering*, ISSN 0140-0118. [Print ed.], May 2015, vol. 53, iss. 5, str. 381-392, ilustr., doi: [10.1007/s11517-015-1247-1](https://doi.org/10.1007/s11517-015-1247-1). [COBISS.SI-ID [13926683](#)], [JCR, SNIP, WoS do 1. 1. 2019: št. citatov (TC): 10, čistih citatov (CI): 10, Scopus do 28. 5. 2019: št. citatov (TC): 13, čistih citatov (CI): 13]
4. **BROJAN, Miha**, VELDIN, Tomo, BRANK, Boštjan. Finite element based on a reduced Kirchhoff-Love shell model for simulation of soft bilayers. V: *Book of abstracts*. Warszawa: Polish Academy of Sciences. cop. 2018, str. 486-487, ilustr. <http://www.solmech2018.ippt.pan.pl/BookOfAbstracts.pdf>. [COBISS.SI-ID [8555617](#)]
5. ČEBRON, Matjaž, **BROJAN, Miha**. *Trdnostna analiza lopatice D350*. Ljubljana: Fakulteta za strojništvo, Laboratorij za nelinearno mehaniko, 2017. [8] f., ilustr. [COBISS.SI-ID [15758875](#)]

Jaka Tušek:

1. PORENTA, Luka, TROJER, Jonas, BROJAN, Miha, **TUŠEK, Jaka**. Experimental investigation of buckling stability of superelastic Ni-Ti tubes under cyclic compressive loading : towards defining functionally stable tubes for elastocaloric cooling. *International journal of solids and structures*. [Print ed.]. Dec. 2022, vol. 256, str. 1-15, ilustr. ISSN 0020-7683. <https://www.sciencedirect.com/science/article/pii/S0020768322004012> DOI:10.1016/j.ijsolstr.2022.111948. [COBISS.SI-ID [122518275](#)].
2. AHČIN, Žiga, DALL'OLIO, Stefano, ŽEROVNIK, Andrej, ŽVAR BAŠKOVIČ, Urban, PORENTA, Luka, KABIRIFAR, Parham, CERAR, Jan, ZUPAN, Samo, BROJAN, Miha, KLEMENC, Jernej, **TUŠEK, Jaka**. High-performance cooling and heat pumping based on fatigue-resistant elastocaloric effect in compression. *Joule*. Oct. 2022, vol. 6, nr. 10, str. 2338-2357, ilustr. ISSN 2542-4351. <https://www.sciencedirect.com/science/article/pii/S2542435122004123> , <https://repozitorij.uni-lj.si/IzpisGradiva.php?id=142647> , DOI: 10.1016/j.joule.2022.08.011. [COBISS.SI-ID [122510851](#)].
3. 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](#)].

4. PORENTA, Luka, KABIRIFAR, Parham, ŽEROVNIK, Andrej, ČEBRON, Matjaž, ŽUŽEK, Borut, DOLENEC, Matej, BROJAN, Miha, **TUŠEK, Jaka**. Thin-walled Ni-Ti tubes under compression: ideal candidates for efficient and fatigue-resistant elastocaloric cooling. Applied materials today. Sep. 2020, vol. 20, f. 1-9, ilustr. ISSN 2352-9415.
<https://www.sciencedirect.com/science/article/pii/S235294072030158X> ,
<https://repozitorij.uni-lj.si/IzpisGradiva.php?id=116755> , DOI: 10.1016/j.apmt.2020.100712. [COBISS.SI-ID [18414339](#)].

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<https://www.sciencedirect.com/science/article/pii/S135964541830226X> ,
<https://repozitorij.uni-lj.si/IzpisGradiva.php?id=127889> , DOI: 10.1016/j.actamat.2018.03.032. [COBISS.SI-ID [15964187](#)].