



Faculty of Engineering  
University of Kragujevac



Ministry of Science, Technological  
Development and Innovation

**10<sup>th</sup> International Congress  
Motor Vehicles & Motors 2024  
ECOLOGY -  
VEHICLE AND ROAD SAFETY  
- EFFICIENCY  
Proceedings**



University of Kragujevac



Department for Motor Vehicles  
and Motors



International Journal for Vehicle  
Mechanics, Engines and  
Transportation Systems

October 10<sup>th</sup> - 11<sup>th</sup>, 2024  
Kragujevac, Serbia

**10<sup>th</sup> International Congress  
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October 10<sup>th</sup> - 11<sup>th</sup>, 2024  
Kragujevac, Serbia

*Publisher:* Faculty of Engineering, University of Kragujevac  
Sestre Janjić 6, 34000 Kragujevac, Serbia

*For Publisher:* Prof. Slobodan Savić, Ph.D.  
Dean of the Faculty of Engineering

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*Cover:* Nemanja Lazarević

*USB printing:* Faculty of Engineering, University of Kragujevac, Kragujevac

*ISBN:* 978-86-6335-120-2

*Year of publication:* 2024.

*Number of copies printed:* 100

CIP - Каталогизација у публикацији  
Народна библиотека Србије, Београд

CIP - Каталогизација у публикацији Народна библиотека Србије, Београд

629.3(082)(0.034.2)  
621.43(082)(0.034.2)

INTERNATIONAL Congress Motor Vehicles and Motors (10 ; 2024 ; Kragujevac)  
Ecology - Vehicle and Road Safety - Efficiency [Elektronski izvor] : proceedings /  
[10th] international congress Motor vehicles & motors 2024, October 10th - 11th,  
2024 Kragujevac, Serbia ; [editors Jasna Glišović, Ivan Grujić]. - Kragujevac :  
University, Faculty of Engineering, 2024 (Kragujevac : University, Faculty of  
Engineering). - 1 USB fleš memorija ; 1 x 1 x 6 cm

Sistemski zahtevi: Nisu navedeni. - Nasl. sa nasl. strane dokumenta. - Tiraž 100.

-

Bibliografija uz svaki rad.

ISBN 978-86-6335-120-2

a) Моторна возила -- Зборници b) Мотори са унутрашњим сагоревањем --  
Зборници

COBISS.SR-ID 153339657

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*Publishing of this USB Book of proceedings was supported by  
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## PREDGOVOR

U oktobru se na Fakultetu inženjerskih nauka Univerziteta u Kragujevcu tradicionalno održava skup istraživača i naučnika koji se bave proučavanjem motornih vozila, motora i drumskog saobraćaja. Od 1979. do 2004. godine održano je trinaest bienalnih MVM simpozijuma koji su 2006. prerasli u Međunarodni kongres MVM. Od tada je održano devet MVM kongresa, a oktobra 2024. godine Fakultet inženjerskih nauka je organizovao deseti međunarodni kongres MVM od 10. do 11. oktobra 2024. godine.

Na deseti kongres Motorna vozila i motori, MVM2024 dostavljen je veliki broj naučnih radova iz Srbije i inostranstva. Kongres tradicionalno podržavaju Ministarstvo za nauku, tehnološki razvoj i inovacije Republike Srbije, Univerzitet u Kragujevcu, Fakultet inženjerskih nauka i međunarodni časopis „Mobility and Vehicle Mechanics“.

Tema Kongresa MVM 2024 bila je „Ekologija – Bezbednost vozila i na putevima – Efikasnost“. Tokom ovog istraživačkog putovanja, učesnici su puno naučili kroz rad na različitim sekcijama, koje su pokrivale širok spektar tema u vezi sa inženjerstvom u automobilske industriji, od fundamentalnih istraživanja do industrijskih primena, naglašavaju interakciju između vozača, vozila i životne sredine i stimulišući naučnu interakciju i saradnju.

Međunarodni naučni odbor u saradnji sa organizacionim odborom izradio je podsticajan naučni program. Program je ponudio preko 54 prezentacije radova, uključujući predavanja po pozivu i radove u sekcijama. Prezentacije na ovom kongresu obuhvatile su aktuelna istraživanja u oblasti motornih vozila i motora sprovedena u 12 zemalja iz celog sveta.

Zadovoljstvo nam je bilo što su nam uvodničari bili profesor Emrulah Hakan Kaleli (sa Tehničkog univerziteta Yıldız, Turska), profesor Ralph Putz (sa Univerziteta Landshut UAS, Nemačka) i profesori Nenad Miljić i Slobodan Popović (sa Univerziteta u Beogradu, Srbija). Izazovi i rešenja u korišćenju vodonika kao goriva za motore sa unutrašnjim sagorevanjem, korišćenje aditiva nanoborne kiseline dodatog u motorno ulje, kao i evropska politika o budućoj mobilnosti na putevima su bile teme uvodnih predavanja.

Sigurni smo da je ovaj program pokrenuo živu diskusiju i podstakao istraživače na nova dostignuća.

10. Kongres MVM 2024. finansijski je podržalo Ministarstvo za nauku, tehnološki razvoj i inovacije Republike Srbije.

Zahvaljujemo se iskusnim i mladim istraživačima koji su prisustvovali i prezentovali svoju stručnost i inovativne ideje na našem kongresu.

Posebnu zahvalnost dugujemo članovima međunarodnog naučnog odbora i svim recenzentima za njihov značajan doprinos visokom nivou kongresa.

Naučni i organizacioni komitet Kongresa MVM2024

## FOREWARD

In October, the Faculty of Engineering University of Kragujevac traditionally holds gatherings of researchers and academics who study motor vehicles, engines and road traffic. From 1979 to 2004, thirteen, biennial MVM Symposiums have been held and they grew into an International Congress MVM in 2006. Since then, ninth MVM Congresses have been held, and in October 2024, the Faculty of Engineering organized the tenth International Congress MVM from 10th to 11th October 2024.

A large number of scientific papers from the Serbia and abroad were submitted to the tenth Congress "MVM2024". Congress is traditionally supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, University of Kragujevac, Faculty of Engineering and the International Journal "Mobility and Vehicle Mechanics".

The theme of the Congress MVM 2024 was "Ecology - Vehicle and Road Safety - Efficiency". Along this journey we learned from the various sessions, which broadly cover a wide range of topics related to automotive engineering from fundamental research to industrial applications, highlight the interaction between the driver, vehicle and environment and stimulate scientific interactions and collaborations.

The International Scientific Committee in collaboration with the Organising Committee built up a stimulating scientific program. The program offered over 54 presentations, including key-note speakers and paper sessions. The presentations to this conference covered current research in motor vehicle and motors conducted in 12 countries from all over the world.

We were pleased to have professor Emrullah Hakan Kaleli (from Yıldız Technical University, Türkiye), professor Ralph Pütz (from Landshut University UAS, Germany) and professors Nenad Miljić and Slobodan Popović (from University of Belgrade, Serbia) as the keynote speakers, addressing Challenges and solutions in using hydrogen as a fuel for internal combustion engines, using nanoboric acid (nBA) additive added in engine oil, as well as European policy on future road mobility.

We are sure this program will trigger lively discussion and will project researchers to new developments.

The 10th Congress MVM 2024 was financially supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia.

We would like to thank experienced and young researchers, for attending and bringing their expertise and innovative ideas to our conference.

Special thanks are due to the International Scientific Board Members and all reviewers for their significant contribution in the high level of the conference.

Scientific and Organizational committee of Congress MVM2024

# CONTENT

## INTRODUCTORY LECTURES

MVM2024-IL1	Ralph Pütz	<b>EU ENERGY AND PROPULSION TRANSITIONS IN THE MOBILITY SECTOR OF GERMANY – A REALIZABLE STRATEGY OR EVEN RATHER IDEOLOGICAL ASTRAY?</b>	3
MVM2024-IL2	Nenad Miljić Slobodan Popović	<b>HYDROGEN AND INTERNAL COMBUSTION ENGINES – STATUS, PERSPECTIVES AND CHALLENGES IN PROVIDING HIGH EFFICIENCY AND CO2 FREE POWERTRAIN FOR FUTURE</b>	13
MVM2024-IL3	Hakan Kaleli Selman Demirtaş Veli Uysal	<b>NANOSCALE TRIBOLOGICAL INFLUENCE OF NBA ADDED IN ENGINE OIL FOR FRICTION AND WEAR BEHAVIOUR IN DIESEL ENGINE CYLINDER LINER SURFACE RUBBED UNDER 1ST AND 2ND PISTON RINGS</b>	35

## SECTION A

### Power Train Technology

MVM2024-008	Vanja Šušteršič Vladimir Vukašinić Dušan Gordić Mladen Josijević	<b>APPLICATION OF HYDROSTATIC TRANSMISSION IN MOBILE MACHINE</b>	55
MVM2024-010	Miloš Maljković Ivan Blagojević Branko Miličić Dragan Stamenković	<b>TOWARDS AN ENERGY EFFICIENT OPERATION OF A SUPERCAPACITOR ELECTRIC BUS</b>	65
MVM2024-013	Zoran Masoničić Siniša Dragutinović Aleksandar Davinić Slobodan Savić Radivoje Pešić	<b>SOME ASPECTS OF COMBUSTION MODEL VARIATION ONTO FLAME PROPAGATION AND EXHAUST EMISSIONS OF IC ENGINES</b>	75
MVM2024-016	Predrag Mrđa Marko Kitanović Slobodan Popović Nenad Miljić Nemanja Bukušić	<b>MATHEMATICAL MODELING OF AN ELECTRONIC THROTTLE VALVE USING NARX NEURAL NETWORKS</b>	83
MVM2024-018	Nemanja Bukušić Predrag Mrđa Marko Kitanović Nenad Miljić Slobodan Popović	<b>GASOLINE DIRECT INJECTION STRATEGY ANALYSIS FOR IMPROVED COMBUSTION</b>	93
MVM2024-020	Nenad Miljić Predrag Mrđa Mihailo Olđa Slobodan J. Popović Marko Kitanović	<b>THE METHOD AND INSTRUMENTATION FOR ENGINE POSITIONING ON A TESTBED WITH FAST SHAFT ALIGNMENT</b>	103



MVM2024-026	Minja Velemir Radović Danijela Nikolić Nebojša Jurišević Saša Jovanović	<b>APPLICATION OF WASTE PLASTIC OIL IN THE MODERN AUTOMOTIVE INDUSTRY</b>	111
MVM2024-031	Miroljub Tomić Dragan Knežević Miloljub Štavljanin	<b>CYLINDER DEACTIVATION IN IC ENGINES IN CYLINDER PROCESS SIMULATION</b>	123
MVM2024-037	Marko Nenadović Dragan Knežević Željko Bulatović	<b>CHARACTERISTICS OF TORSIONAL OSCILLATIONS OF PERKINS 1104 ENGINE CRANKSHAFT</b>	131
MVM2024-038	Marko Nenadović Dragan Knežević Željko Bulatović	<b>ANALYSIS OF CRANKSHAFT TORSIONAL OSCILLATION DUMPER FOR ENGINE V-46-6</b>	141
MVM2024-047	Attila Kiss Bálint Szabó Zoltán Weltsch	<b>THE SAFETY ISSUES OF HYDROGEN-GASOLINE DUAL-FUEL INJECTION IN NATURAL ASPIRATED INTERNAL COMBUSTION ENGINES</b>	153
MVM2024-049	Ivan Grujic Aleksandar Davinic Nadica Stojanovic Zeljko Djuric Marko Lucic Radivoje Pesic	<b>THE NUMERICAL INVESTIGATION OF THE WORKING CYCLE OF DUAL FUEL IC ENGINE</b>	163

## **SECTION B Vehicle Design and Manufacturing**

MVM2024-005	Gordana Bogdanović Dragan Čukanović Aleksandar Radaković Milan T. Đorđević Petar Knežević	<b>FUNCTIONALLY GRADED MATERIALS IN AUTOMOTIVE INDUSTRY-MODELLING AND ANALYSIS OF FG PLATE ON ELASTIC FOUNDATION</b>	171
MVM2024-006	Dušan Arsić Djordje Ivković Dragan Adamović Vesna Mandić Marko Delić Andjela Mitrović Nada Ratković	<b>APPLICATION OF HIGH STRENGTH STEELS IN AUTOMOTIVE INDUSTRY</b>	179
MVM2024-011	Saša Vasiljević Jasna Glišović Marko Maslač Milan Đorđević Sonja Kostić Dobrivoje Čatić	<b>TIRE WEAR: VEHICLE SAFETY AND ENVIRONMENTAL PROBLEM</b>	187
MVM2024-012	Zorica Đorđević Sonja Kostić Saša Jovanović Danijela Nikolić	<b>THE INFLUENCE OF FIBER ORIENTATION ANGLE ON THE STABILITY OF A COMPOSITE DRIVE SHAFT</b>	199
MVM2024-014	Vojislav Filipovic Milan Matijevic Dragan Kostic	<b>DIGITAL PREVIEW CONTROLLER DESIGN USING REINFORCEMENT LEARNING</b>	205
MVM2024-015	Milan Matijevic Vojislav Filipovic Dragan Kostic	<b>ITERATIVE LEARNING (ILC) IN MANUFACTURING SYSTEMS: DESIGN OF ILC ALGORITHMS AND OVERVIEW OF MODEL INVERSION TECHNIQUES FOR ILC SYNTHESIS</b>	213

MVM2024-017	Marko Delić Vesna Mandić Dragan Adamović Dušan Arsić Đorđe Ivković Nada Ratković	<b>ANALYSIS OF PHOTOGRAMMETRY APPLICATION POSSIBILITIES FOR REVERSE ENGINEERING OF COMPONENTS IN THE AUTO INDUSTRY</b>	229
MVM2024-023	Dániel Kecskés László Tóth István Péter Szabó	<b>STRENGTH TESTING OF 3D PRINTED SPECIMENS</b>	235
MVM2024-027	Milan Stanojević Milan Bukvić Saša Vasiljević Lozica Ivanović Blaža Stojanović	<b>RESEARCH METHODS IN THE DESIGN PROCESS OF HYDRAULIC SYSTEMS WITH CYCLOID TEETH</b>	247
MVM2024-028	Dragan Adamovic Vesna Mandic Nada Ratkovic Dusan Arsic Djordje Ivkovic Marko Delic Marko Topalovic	<b>MODERN MATERIALS IN AUTOMOTIVE INDUSTRY - REVIEW</b>	255
MVM2024-029	Dragan Adamović Fatima Živić Nikola Kotorčević Nenad Grujović	<b>REVIEW OF THE USE OF NANOTECHNOLOGIES AND NANOMATERIALS IN THE AUTOMOTIVE INDUSTRY: DEVELOPMENT, APPLICATIONS AND FUTURE DIRECTIONS</b>	269
MVM2024-032	Nada Ratković Dragan Adamović Srbislav Aleksandrović Vesna Mandić Dušan Arsić Marko Delić Živana Jovanović Pešić	<b>ADVANCED WELDING TECHNOLOGIES: FSW IN AUTOMOTIVE MANUFACTURING</b>	281
MVM2024-035	Milan Bukvić Sandra Gajević Slavica Miladinović Saša Milojević Momčilo Đorđević Blaža Stojanović	<b>CHARACTERISTICS AND APPLICATION OF POLYMER COMPOSITES IN THE AUTOMOTIVE INDUSTRY</b>	289
MVM2024-036	Gordana Bogdanović Aleksandar Radaković Dragan Čukanović Nikola Velimirović Petar Knežević	<b>SHAPE FUNCTION OPTIMIZATION FOR STATIC ANALYSIS OF COMPOSITE MATERIALS USED IN AUTOMOTIVE INDUSTRY</b>	295
MVM2024-039	Igor Saveljić Slavica Mačužić Saveljić Nenad Filipović	<b>THE MODERN APPROACH TO PROBLEM- SOLVING IN MECHANICAL ENGINEERING - APPLICATION OF ARTIFICIAL INTELLIGENCE</b>	303
MVM2024-040	Slavica Mačužić Saveljić Igor Saveljić Jovanka Lukić	<b>DETERMINATION OF THE SEAT-TO-HEAD TRANSFER FUNCTION AND INFLUENCING FACTORS ON COMFORT UNDER VERTICAL RANDOM VIBRATIONS</b>	309
MVM2024-041	Dobrivoje Čatić Saša Vasiljević Živana Jovanović Pešić Vladimir Čatić	<b>DISC BRAKE FAILURE ANALYSIS OF THE MOTOR VEHICLE BRAKING SYSTEM</b>	315

MVM2024-048	Isak Karabegović Ermin Husak Edina Karabegović Mehmed Mahmić	<b>DEVELOPMENT AND IMPLEMENTATION OF ADVANCED ROBOTICS IN THE AUTOMOTIVE AND ELECTRO-ELECTRONIC INDUSTRY OF CHINA</b>	321
MVM2024-051	Jasna Glišović Saša Vasiljević Jovanka Lukić Danijela Miloradović	<b>SUBSYSTEM AND SYSTEM ANALYSIS OF BRAKE WEAR PARTICLES FOR PREDICTION AND CONTROL OF THE TRAFFIC NON- EXHAUST EMISSION</b>	331
MVM2024-052	Dobrivoje Čatić Vladimir Čatić	<b>DETERMINING THE RELIABILITY OF BRAKE BOOSTERS IN LIGHT COMMERCIAL VEHICLES</b>	343
MVM2024-053	Nikola Komatina Danijela Tadić Marko Džapan	<b>QUANTITATIVE ANALYSIS OF NONCONFORMING PRODUCTS: A CASE STUDY IN THE AUTOMOTIVE INDUSTRY</b>	349
MVM2024-054	Danijela Miloradović Jasna Glišović Jovanka Lukić Nenad Miloradović	<b>SUSPENSION RATIOS OF MACPHERSON STRUT SUSPENSION</b>	357
MVM2024-056	Nenad Miloradović Rodoljub Vujanac	<b>INFLUENCE OF SELECTION OF MATERIAL HANDLING DEVICES ON SOLUTION FOR WAREHOUSE SYSTEM IN AUTOMOTIVE INDUSTRY</b>	369
MVM2024-057	Nenad Petrović Strahinja Milenković Živana Jovanović Pešić Nenad Kostić Nenad Marijanović	<b>DETERMINING 3D PRINTED HOUSING DIAMETERS FOR PRESS-FITTING STANDARD BALL BEARINGS</b>	379

## SECTION C

### Vehicle Dynamics and Intelligent Control Systems

MVM2024-002	Mihai Blaga	<b>VOLVO FH POWERTRAIN, VEHICLE ENGINE DIAGNOSTICS</b>	387
MVM2024-007	Abdeselem Benmeddah Momir Drakulić Aleksandar Đurić Sreten Perić	<b>MODELING AND VALIDATION OF TRUCK SUSPENSION SYSTEMS USING ADAMS SOFTWARE</b>	401
MVM2024-030	Vesna Ranković Andrija Đonić Tijana Geroski	<b>ROAD TRAFFIC ACCIDENTS PREDICTION USING MACHINE LEARNING METHODS</b>	409
MVM2024-034	Vasko Changoski Igor Gjurkov Vase Janushevska	<b>HANDLING AND STABILITY ANALYSIS OF AN AUTOMATED VEHICLE WITH INTEGRATED FOUR-WHEEL INDEPENDENT STEERING (4WIS)</b>	417
MVM2024-042	Bojana Bošković Nadica Stojanović Ivan Grujić Saša Babić Branimir Milosavljević	<b>THE INFLUENCE OF THERMAL STRESS OF DISC BRAKES ON VEHICLE DECELERATION</b>	431
MVM2024-046	Andjela Mitrović Vladimir Milovanović Nebojša Hristov Damir Jerković Mladen Josijević Djordje Ivković	<b>ANALYSIS OF PLACING ADDITIONAL SUPPORTS OF THE INTEGRATED ARTILLERY SYSTEM CALIBER 130 mm</b>	439

**SECTION D**  
**Driver/Vehicle Interface, Information and Assistance Systems**

MVM2024-001	Miroslav Demić Mikhail P. Malinovsky	<b>INVESTIGATION OF TORSIONAL VIBRATIONS OF THE STEERING SHAFT FROM THE ASPECT OF MINIMAL DRIVER-HAND FATIGUE IN HEAVY MOTOR VEHICLES</b>	451
MVM2024-009	Mikhail P. Malinovsky Miroslav Demić Evgeny S. Smolko	<b>TECHNICAL SOLUTIONS FOR CATASTROPHIC EXTENT OF THE HUMAN FACTOR IN DRIVERS TRAINING AND STRUCTURAL SAFETY OF BUSES AND HEAVY VEHICLES</b>	459
MVM2024-050	Jovanka Lukić Danijela Miloradović Jasna Glišović	<b>MASKING EFFECTS UNDER DUAL AXIS WHOLE BODY VIBRATION</b>	477

**SECTION E**  
**Transport Challenges in Emerging Economies**

MVM2024-004	Slobodan Mišanović	<b>PERFORMANCES OF FAST CHARGERS FOR ELECTRIC BUSES IN BELGRADE ON THE EKO2 LINE</b>	485
MVM2024-019	Siniša Dragutinović Zoran Masonic Aleksandar Davinić Slobodan Savić Radivoje Pešić	<b>APPLICATION OF THE AHP METHOD FOR THE ASSESMENT OF INFLUENTIAL CRITERIA IN RISK ANALYSIS OF ROAD TRANSPORT OF DANGEROUS GOODS</b>	493
MVM2024-021	Željko Đurić Snežana Petković Valentina Golubović Bugarski Nataša Kostić	<b>METHODS FOR CATEGORIZING ROAD TUNNELS ACCORDING TO DANGEROUS GOODS REGULATIONS</b>	501
MVM2024-025	Franci Pušavec Janez Kopač	<b>TRAFFIC HAZARD DUE TO HIGH CENTRE OF GRAVITY</b>	511
MVM2024-043	Alexander Koudrin Sergey Shadrin	<b>DEVELOPMENT OF AN ENERGY-EFFICIENT CONTROL SYSTEM FOR CONNECTED, HIGHLY AUTOMATED VEHICLES</b>	517
MVM2024-055	Marko Miletić Ivan Miletić Robert Ulewich Ružica Nikolić	<b>EV CHARGING STATIONS: CURRENT SITUATION AND FUTURE PERSPECTIVES</b>	527



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## FUNCTIONALLY GRADED MATERIALS IN AUTOMOTIVE INDUSTRY-MODELLING AND ANALYSIS OF FG PLATE ON ELASTIC FOUNDATION

**ABSTRACT:** Due to extensive application of composite materials in automotive industry projects, the focus of paper is on functionally graded materials as a modern composite. In the introductory section of the paper, the basic concept of the aforementioned materials is described, the main advantages and disadvantages are given, as well as examples of their application in various fields of automotive sector. A systematic and practical approach for modelling, designing and analysis of functionally graded plate on elastic foundations is discussed. Three simple elastic foundation models with constant parameters have been analysed: Winkler foundation, Pasternak foundation as well as Kerr foundation. The formulation of the Winkler/Pasternak/Kerr foundation models is studied analytically. On the basis of the described theoretical formulations, numerical examples of the bending of functionally graded plates on elastic foundation are done. The difference between three models of elastic foundation is also discussed by comparing their results. Finally, based on obtained results conclusions and the recommendations for further study are given.

**KEYWORDS:** functionally graded material, elastic foundation, bending analysis

### INTRODUCTION

**Functionally Graded Materials (FGM)** are advanced composite materials characterized by gradual variations in composition, structure and properties through volume. It results in a change of the material's properties, such as mechanical, thermal, electrical, or optical characteristics. These variations are often engineered to optimize the material's performance in specific applications, combining the benefits of different materials in a single component. FGM are designed so that their properties change gradually, rather than abruptly, across the material. This can be in one direction (unidirectional gradient) or multiple directions, depending on the design requirements. The gradient can be in terms of composition, microstructure, or porosity. The composition of FGM can vary between two or more materials, such as metals, ceramics, polymers, or composites. For example, one side of an FGM could be made of

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a metal, providing ductility, while the other side could be ceramic, offering heat resistance. By varying the composition and structure, FGM can be tailored to meet specific functional requirements. This makes them ideal for applications where traditional homogeneous materials might fail or be less efficient.

Finally, it can be said that FGM has significant advantages over conventional materials as:

- **Stress reduction** - the gradual change in properties reduces stress concentrations, particularly in applications involving thermal or mechanical loads.
- **Improved durability** - FGM often have better wear, corrosion, and thermal resistance due to their tailored properties.
- **Design flexibility** - engineers can design components with specific property gradients to meet challenging operational conditions.

On the other hand, there are numerous challenges facing the process of designing and manufacturing FGM [1], [2]:

- **Complex manufacturing** - producing FGM can be more complex and expensive than traditional materials.
- **Design and simulation** - designing FGM requires advanced modelling and simulation tools to predict how the gradient will affect the material's overall behaviour.
- **Quality control** - ensuring uniformity and precision in the gradient can be challenging, requiring sophisticated inspection techniques.

The actuality of research into new materials with a special emphasis on functionally graded materials is indicated by a large number of review papers in recent years [3], [4], [5].

## FUNCTIONALLY GRADED MATERIALS IN AUTOMOTIVE INDUSTRY

Functionally graded materials are increasingly being utilized in the automotive industry due to their ability to enhance the performance, safety, and efficiency of vehicles [6]. Some specific examples of FGM applications in the automotive sector are given below (Figure 1):

- *Brake discs and rotors* - FGM are used in brake discs and rotors to improve thermal management and reduce wear. The material gradient allows for high thermal conductivity on the outer surface to quickly dissipate heat, while the inner layers provide mechanical strength and wear resistance. This reduces the risk of thermal cracking and prolongs the life of the brake components.
- *Engine components* - FGM is employed in various engine components, such as pistons, cylinder heads, and valves. The gradient in material properties allows these components to withstand high temperatures and pressures while maintaining strength and durability. For example, a piston made with an FGM can have a high-temperature-resistant ceramic on the top surface, gradually transitioning to a lightweight metal alloy in the core to reduce overall weight and enhance fuel efficiency.
- *Exhaust systems* - FGM are used in exhaust systems, particularly in catalytic converters and exhaust manifolds. The gradient material design can help manage thermal stresses due to the high temperatures and corrosive environment. FGM can improve the durability and efficiency of the catalytic converter by having a ceramic layer on the interior for heat resistance and a metal exterior for structural support.
- *Turbine blades in turbochargers* - FGM are used in the turbine blades of turbochargers. The material gradient allows the turbine blades to withstand the extreme temperatures and stresses caused by high-speed rotation. The high-temperature-resistant ceramic on the surface gradually transitions to a tougher metal alloy, providing both heat resistance and mechanical strength.
- *Lightweight structural components* - FGM are utilized in various lightweight structural components, such as body panels and chassis parts. By using FGM, manufacturers can create components that are both strong and lightweight. For instance, a panel can have a tough, impact-resistant surface with a lightweight, stiff core, optimizing the strength-to-weight ratio. This contributes to improved fuel efficiency and vehicle performance.
- *Crashworthiness and impact protection* - FGM are used in areas of the vehicle that are designed to absorb energy during a crash, such as bumper systems and door panels. The material gradient can be tailored to gradually absorb and dissipate impact energy, improving the vehicle's crashworthiness. The outer layers can be made stiffer to absorb initial impact, while the inner layers are more compliant, helping to reduce the force transmitted to the occupants.
- *Heat shields* - FGM are used in heat shields that protect other components from the high temperatures of the engine or exhaust. The graded material can provide high thermal resistance on the side facing the heat source and a lower thermal conductivity on the opposite side, protecting the adjacent components from heat damage and reducing heat transfer to the vehicle cabin.
- *Advanced coatings for wear and corrosion resistance* - FGM are applied as coatings on various automotive parts, such as gears, shafts, and bearings. These coatings can provide a hard, wear-resistant outer layer with a tougher, more ductile inner layer, improving both the durability and fatigue resistance of the components. This is particularly important for parts subjected to cyclic loading and harsh environments.

- *Battery thermal management in electric vehicles* - FGM are being explored for use in the thermal management systems of batteries in electric vehicles (EVs). The graded material can help manage the temperature within the battery pack more effectively, ensuring uniform temperature distribution and preventing overheating, which is crucial for battery efficiency and safety.

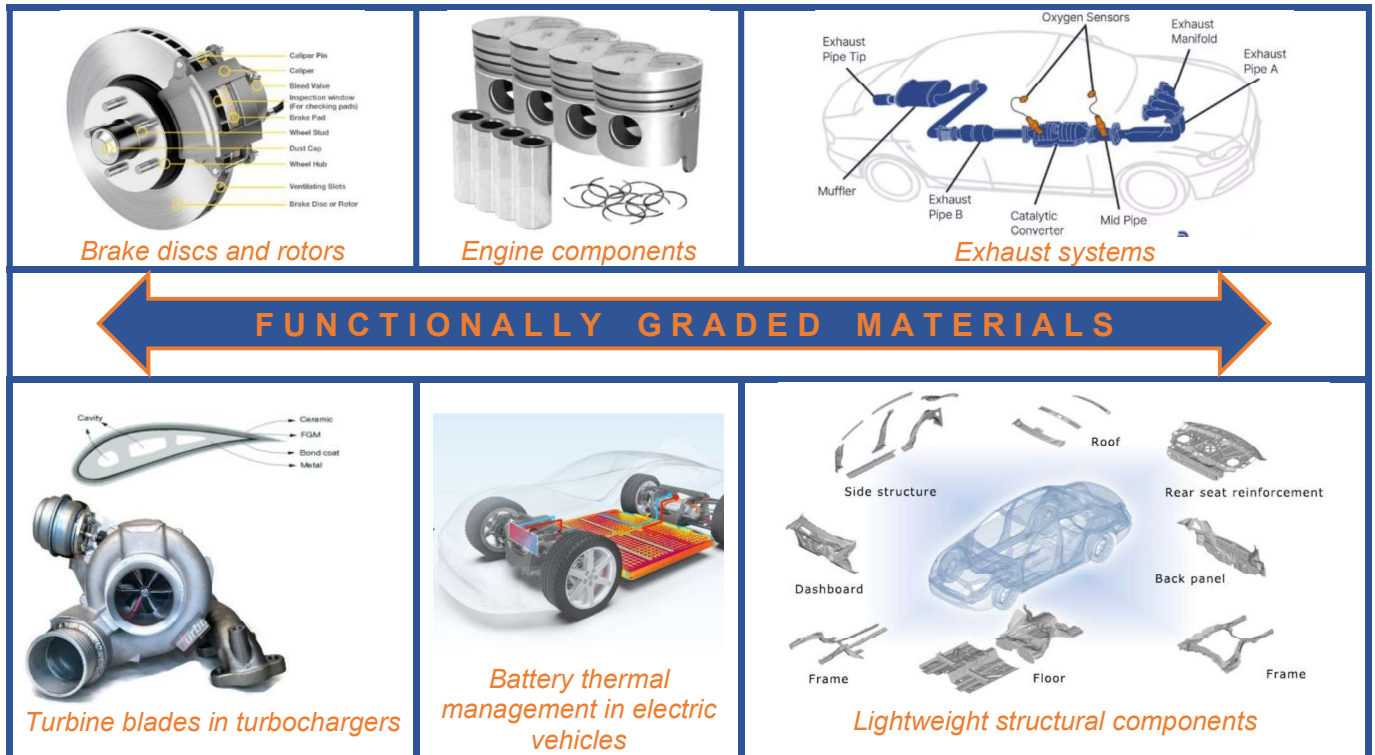


Figure 1 FGM applications in the automotive sector

## MODELLING OF FG PLATE ON ELASTIC FOUNDATION

Modelling functionally graded (FG) plate on an elastic foundation involves understanding the gradation of material properties within the plate and accurately representing the foundation's support behaviour using appropriate models. The complexity of the model and the chosen foundation directly influence the accuracy and applicability of the analysis, making it essential to choose the right model based on the specific requirements of the problem.

Functionally graded materials are advanced composite materials where the material properties (e.g., Young's modulus, density, thermal conductivity) vary continuously along one or more dimensions, typically according to a specific gradient function. This gradual change in properties is often achieved by varying the volume fraction of two or more constituent materials. In an FGM plate, the material properties vary continuously across the thickness, making it possible to optimize the plate's performance under different loading conditions. For instance, one surface of the plate might be made of a metal for high strength, while the opposite surface might be ceramic for high-temperature resistance. The gradation is usually in the thickness direction ( $z$ -axis), with properties typically following a power-law, exponential, or sigmoid function [7]. A common power-law distribution of the volume fraction  $V(z)$  of the constituents can be expressed as:

$$V_i = \left( \frac{1}{2} + \frac{z}{h} \right)^p \quad (1)$$

and mechanical properties of the FGM in the thickness direction of the plate

$$P(z) = P_m + P_{cm} V_f, \quad P_{cm} = P_c - P_m \quad (2)$$

where is:

$h$  - the total thickness of the plate

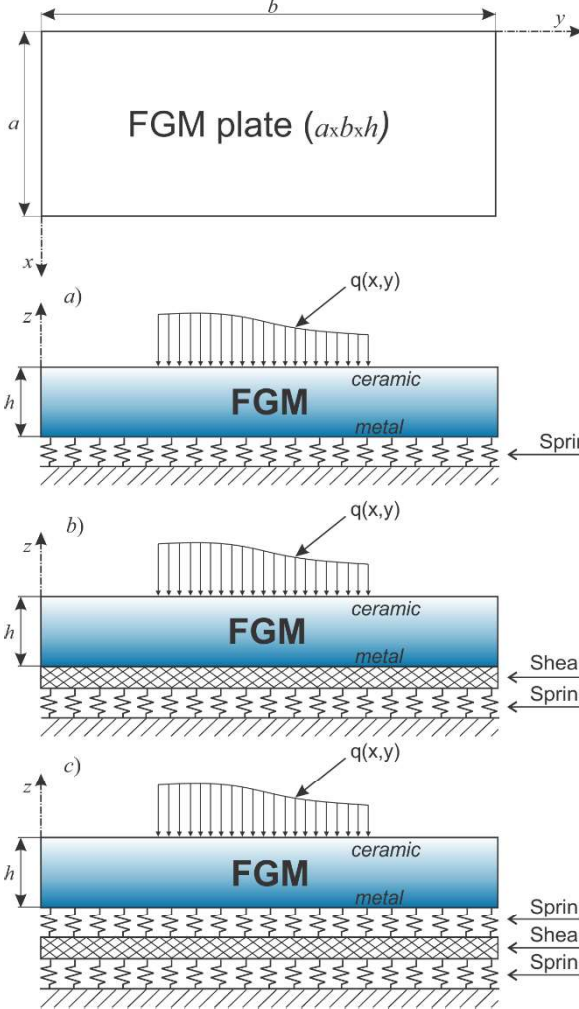
$z$  - the coordinate through the thickness

$p$  - the material gradation index that controls the material distribution

$P(z)$ ,  $P_m$ ,  $P_c$  - mechanical properties of arbitrary cross section „ $z$ “, metal, ceramic, respectively

The elastic foundation provides the reactive support to the FG plate whereby different models can be used to describe the foundation behaviour (Figure 2), [8], [9], [10], [11]:

- **Winkler foundation** - represents the foundation as a series of independent, linear elastic springs. The foundation reaction is proportional to the local displacement of the plate, but it does not account for shear interactions between adjacent points.
- **Pasternak foundation** - adds a shear layer to the Winkler model, accounting for the shear interaction between adjacent points on the foundation. This model is more suitable when the foundation behaves like a continuous medium rather than discrete springs.
- **Kerr foundation** - incorporates the vertical displacement, shear interaction, and bending stiffness of the foundation, providing a more accurate representation, especially for thick or complex foundation systems.



$q_e(x,y)$  - foundation reaction

$U_e$  - strain energy of the elastic foundation

$$q_e^{Winkler} = k_s w$$

$$U_e^{Winkler} = \int_A \frac{1}{2} k_s w^2 dA$$

$$q_e^{Pasternak} = k_s w - G_p \nabla^2 w, \quad \nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$$

$$U_e^{Pasternak} = \frac{1}{2} \int_A \left\{ k_s w^2 + G_p \left[ \left( \frac{\partial w}{\partial x} \right)^2 + \left( \frac{\partial w}{\partial y} \right)^2 \right] \right\} dA$$

$$q_e^{Kerr} = \frac{k_s k_b}{k_s + k_b} w - \frac{G_p k_b}{k_s + k_b} \nabla^2 w$$

$$U_e^{Kerr} = \frac{1}{2} \int_A \left\{ \frac{k_s k_b}{k_s + k_b} w^2 + \frac{G_p k_b}{k_s + k_b} \left[ \left( \frac{\partial w}{\partial x} \right)^2 + \left( \frac{\partial w}{\partial y} \right)^2 \right] \right\} dA$$

**Figure 2** Different models of FG plate on elastic foundation: a) Winkler foundation, b) Pasternak foundation, c) Kerr foundation

According to the higher-order shear deformation theory (HSDT), the initial step in defining the kinematic relations between displacement and strain involves the assumed forms of the displacement components:

$$u = u_0(x,y) - z w_{0,x} + f(z) \theta_x, \quad v = v_0(x,y) - z w_{0,y} + f(z) \theta_y, \quad w = w_0(x,y),$$

$$f(z) = z \left( \cosh\left(\frac{z}{h}\right) - 1,388 \right) - \text{shape function} \quad (3)$$

To define the components of unit loads, it is essential to apply the relationships between displacements and strains according to the linear theory of elasticity. The elastic constitutive relations for FGM are given as follows:

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xz} \\ \tau_{yz} \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} C_{11}(z) & C_{12}(z) & 0 & 0 & 0 \\ C_{12}(z) & C_{22}(z) & 0 & 0 & 0 \\ 0 & 0 & C_{44}(z) & 0 & 0 \\ 0 & 0 & 0 & C_{55}(z) & 0 \\ 0 & 0 & 0 & 0 & C_{66}(z) \end{bmatrix} \begin{Bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \gamma_{xz} \\ \gamma_{yz} \\ \gamma_{xy} \end{Bmatrix} \quad (4)$$

where the coefficients of the constitutive elasticity tensor could be defined through engineering constants:



$$C_{11}(z) = C_{22}(z) = \frac{E(z)}{1-\nu^2}, \quad C_{44}(z) = C_{55}(z) = C_{66}(z) = \frac{E(z)}{2(1+\nu)}, \quad C_{12}(z) = \frac{\nu E(z)}{1-\nu^2} \quad (5)$$

Due to the gradient variation of the plate structure along the z-coordinate, the modulus of elasticity can be defined based on equations (1) and (2) as follows:

$$E(z) = E_m + E_{cm} \left( \frac{1}{2} + \frac{z}{h} \right)^p, \quad E_{cm} = E_c - E_m \quad (6)$$

while  $\nu = \text{const}$  - Poisson's ratio  $\nu$  is considered constant because its variation in the thickness direction of the plate is minimal.

For the bending analysis to be carried out, it is assumed that the plate is subjected to sinusoidal transverse load  $q(x,y)$ . Work under external load is defined as:

$$V = -\frac{1}{2} \int_A q w dA, \quad \text{where is } q(x,y) = q_0 \sin\left(\frac{\pi x}{a}\right) \sin\left(\frac{\pi y}{b}\right) \quad (7)$$

Plate strain energy deformation  $U$  are defined as:

$$U = \int_A (N_{xx} \varepsilon_{xx}^{(0)} + N_{yy} \varepsilon_{yy}^{(0)} + N_{xy} \gamma_{xy}^{(0)} + M_{xx} k_{xx}^{(0)} + M_{yy} k_{yy}^{(0)} + M_{xy} k_{xy}^{(0)} + P_{xx} k_{xx}^{(1)} + P_{yy} k_{yy}^{(1)} + P_{xy} k_{xy}^{(1)} + R_x k_{xz}^{(2)} + R_y k_{yz}^{(2)}) dA \quad (8)$$

while strain energy of the elastic foundation  $U_e$  is defined according Figure 2 depending on the selected model of foundation.

Using the principle on minimum potential energy, the following equation is obtained:

$$\begin{aligned} \delta U + \delta V + \delta U_e = \delta(U + V + U_e) &\equiv \delta \Pi = \int_A (N_{xx} \delta \varepsilon_{xx}^{(0)} + N_{yy} \delta \varepsilon_{yy}^{(0)} + N_{xy} \delta \gamma_{xy}^{(0)} + M_{xx} \delta k_{xx}^{(0)} + M_{yy} \delta k_{yy}^{(0)} + M_{xy} \delta k_{xy}^{(0)} \\ &+ P_{xx} \delta k_{xx}^{(1)} + P_{yy} \delta k_{yy}^{(1)} + P_{xy} \delta k_{xy}^{(1)} + R_x \delta k_{xz}^{(2)} + R_y \delta k_{yz}^{(2)}) dA - \int_A q \delta w dA \\ &+ \int_A \left\{ \frac{k_s k_b}{k_s + k_b} w \delta w + \frac{G_p k_b}{k_s + k_b} \left( \frac{\partial w}{\partial x} \frac{\partial \delta w}{\partial x} + \frac{\partial w}{\partial y} \frac{\partial \delta w}{\partial y} \right) \right\} dA = 0 \end{aligned} \quad (9)$$

$\underbrace{\hspace{10em}}_{\text{Kerr}}$   
 $\underbrace{\hspace{10em}}_{\text{Pasternak} \rightarrow k_b \text{ equal to infinity}}$   
 $\underbrace{\hspace{10em}}_{\text{Winkler} \rightarrow k_b \text{ equal to infinity and } G_p = 0}$

By substituting the strain components and applying the calculus of variations, the following equilibrium equations are obtained:

$$\begin{aligned} \delta u_0: \quad N_{xx,x} + N_{xy,y} &= 0 \\ \delta v_0: \quad N_{yy,y} + N_{xy,x} &= 0 \\ \delta w_0: \quad M_{xx,xx} + 2M_{xy,xy} + M_{yy,yy} + N_{xx} w_{0,xx} + 2N_{xy} w_{0,xy} + N_{yy} w_{0,yy} \\ &+ q - \frac{k_s k_b}{k_s + k_b} w_0 + \frac{G_p k_b}{k_s + k_b} (w_{0,xx} + w_{0,yy}) = 0 \end{aligned} \quad (10)$$

$\underbrace{\hspace{10em}}_{\text{Kerr}}$   
 $\underbrace{\hspace{10em}}_{\text{Pasternak} \rightarrow k_b \text{ equal to infinity}}$   
 $\underbrace{\hspace{10em}}_{\text{Winkler} \rightarrow k_b \text{ equal to infinity and } G_p = 0}$

$$\begin{aligned} \delta \theta_x: \quad P_{xx,x} + P_{xy,y} - R_x &= 0 \\ \delta \theta_y: \quad P_{xy,x} + P_{yy,y} - R_y &= 0 \end{aligned}$$

where:

$$\mathbf{N} = \{N_{xx} \quad N_{yy} \quad N_{xy}\}^T, \quad \mathbf{M} = \{M_{xx} \quad M_{yy} \quad M_{xy}\}^T, \quad \mathbf{P} = \{P_{xx} \quad P_{yy} \quad P_{xy}\}^T, \quad \mathbf{R} = \{R_x \quad R_y\}^T \quad (11)$$

represents the force, moments and higher order moment resultants.

To obtain analytical solutions for the system of equations (10), assumed solution forms and boundary conditions are adopted in accordance with Navier's solution as presented in [12].

## NUMERICAL RESULTS AND DISCUSSION

To apply the theoretical results for simulating engineering problems in MATLAB, a code for analysing FGM plates has been developed, and various numerical examples have been conducted. This chapter will present the results obtained from the bending analysis of FG plates composed of metal (*Al*-Aluminium:  $E_m=0,7 \cdot 10^5$  [MPa],  $\nu=0.3$ ) and ceramic ( $Al_2O_3$ -Alumina:  $E_c=3,8 \cdot 10^5$  [MPa],  $\nu=0.3$ ) constituents.

Normalized values of a vertical displacement  $\bar{w}$  (deflection) for different model of elastic foundation (Winkler/Pasternak/Kerr) and different volume fraction of constituents in FGM (index "p") are given in Table 1. Normalization of the aforementioned value has been conducted according to:

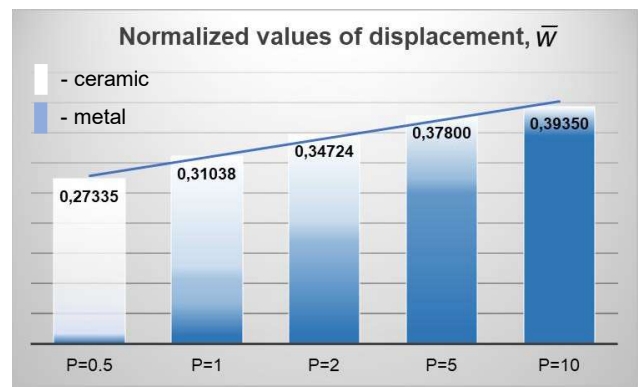
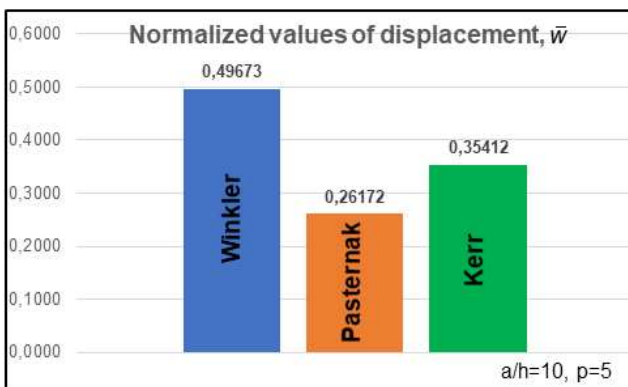
$$\bar{w} = \frac{10E_c h^3}{q_0 a^4} w \left( \frac{a}{2}, \frac{b}{2} \right) \tag{12}$$

**Table 1** Normalized values of displacement of FG square plate on elastic foundation

Theory	$k_s$	$G_p$	$k_b$	a/h	$\bar{w}$				
					FGM plate				
					p = 0,5	p = 1	p = 2	p = 5	p = 10
Winkler	100			5	0,35118	0,41476	0,48331	0,54504	0,57786
				10	0,32053	0,38260	0,44717	0,49673	0,52433
Pasternak	100	10		5	0,21481	0,23704	0,25795	0,27454	0,28263
				10	0,20294	0,22617	0,24728	0,26172	0,26919
Kerr	100	10	100	5	0,27335	0,31038	0,34724	0,37800	0,39350
				10	0,25441	0,29202	0,32819	0,35412	0,36792

Based on the results shown in Table 1, it can be concluded that compared to Winkler's model, the introduction of a shear layer (coefficient  $G_p$ ) in Pasternak's model leads to a decrease in the normalized value of vertical displacement. On the other hand, the introduction of another row of springs (coefficient  $k_b$ ) in Kerr's model leads to an increase in the normalized value of vertical displacement compared to Pasternak's model. In order to get a clear insight on the above mentioned effect of Winkler/Pasternak/Kerr coefficients, Figure 3a shows the comparative normalized displacement values for FG plate  $a/h=10$  and  $p=5$ .

Figure 3b shows the influence of the volume fraction of constituents in FGM on vertical displacement. It should be kept in mind when  $p=0$ , the plate is homogenous, made of ceramics. On the other side, theoretically, when  $p=\infty$  the plate becomes homogenous again, made of metal, although the plate can be considered homogenous even when  $p>10$ . From this it clearly follows that for  $0<p<10$  it is obtained by the FG of the plate. Analysing the diagram, one can clearly see the growth trend of the normalized displacement value with the increase in the volume fraction of metal in the FG plate.



**Figure 3** Comparative results of normalized values of displacement: a) different models of elastic foundation, b) different volume fraction of constituents in FGM

## CONCLUSIONS

The paper highlights the significance and relevance of research on modern composite materials, with a particular focus on functionally graded materials. It underscores the broad range of engineering fields and automotive sectors where FGM are applied. The interaction of FGM plates with an elastic foundation was examined. The fundamental relations defining this interaction are presented by using Winkler's, Pasternak's, and Kerr's mathematical models. Assuming small strains, the kinematic relations between displacement and strain were established using the linear theory of elasticity involves the assumed forms of the displacement components based on higher-order shear deformation theory. Using the strain energy of the plate and the elastic foundation, the equilibrium equations were derived through the principle of minimum potential energy. A procedure for analytically solving these equilibrium equations was developed by applying Navier's assumed displacement forms for a simply supported rectangular FGM plate. These theoretical results were then utilized to obtain numerical results. The analysis of bending in FGM plates resting on an elastic foundation led to the following conclusions:

- the implementation of the shear layer in the Pasternak model results in a reduction of the normalized vertical displacement value when compared to the Winkler model. Conversely, the addition of an extra row of springs in the Kerr model leads to an increase in the normalized vertical displacement value compared to the Pasternak model.
- with the increase in volume fraction of metal in FGM, the value of normalized vertical displacement increases.

## ACKNOWLEDGMENTS

The authors would like to thank the Ministry of Science, Technological Development and Innovation of the Republic of Serbia for funding the scientific research work, contract no. 451-03-65/2024-03/200155, realized by the Faculty of Technical Sciences in Kosovska Mitrovica, University of Pristina.

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