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02	Free vibration, and static deflections of functionally graded plates using the strain approach and strain-based Reissner–Mindlin elements	Constantine, ALGERIA FIRST INTERNATIONAL CONGRESS ON MECHANICAL ENGINEERING	15-16	11	2023	/	/	/	/	Web site : ICME'23: FIRST INTERNATIONAL CONGRESS ON MECHANICAL ENGINEERING - Université Frère Mentouri - Constantine 1 (umc.edu.dz) Email: icme23@crm-constantine.dz

✓ Détails de la conférence

- **Nom de l'événement** : ICME'23 – First International Congress on Mechanical Engineering
- **Lieu** : Université Frère Mentouri – Constantine 1, Constantine, Algérie
- **Dates** : 15–16 novembre 2023

☞ **Page officielle de l'événement sur le site de Université Frère Mentouri – Constantine**
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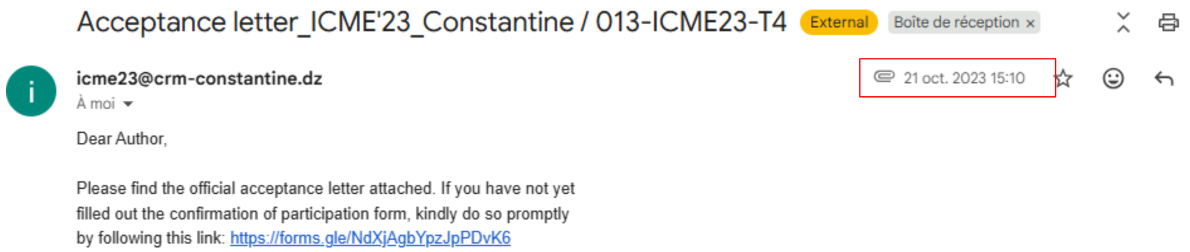
- **Le congrès s'est tenu les 15 et 16 novembre 2023 à Constantine, Algérie.** Fac UMC
- **Email contact** : icme23@crm-constantine.dz
- Lettre d'acceptation a été envoyée par e-mail le **samedi 21 octobre 2023, 15:10**



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ICME23

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The First International Congress on Mechanical Engineering, ICME'23

from November 15th to 16th, 2023

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Certificate
OF PARTICIPATION

ICME23

This certificate proudly presented to

ASSAS TAQIYEDDINE

In oral and technical presentation,
recognition and appreciation of research contribution to

ICME'23 THE FIRST INTERNATIONAL CONGRESS ON MECHANICAL ENGINEERING
CONSTANTINE, ALGERIA
15, 16 NOVEMBER 2023

With the Paper entitled

Free vibration and static deflections of functionally graded plates using the strain approach and strain-based Reissner–Mindlin elements

Dr. BENIA Hadj Mohamed
President of the Congress

Mr. H.M. BENIA
Congress President

Centre of Research in Mechanic
ICME23
First International Congress on Mechanical Engineering
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Pr. BOUCHOUCHA Ali
President of the Congress

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Congress President

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ACCEPTANCE LETTER

15 October 2023

Dear **ASSAS TAQIYEDDINE, Bourezane Messaoud, Chenafi Madjda, Seyfeddine Benabid**

Thank you for your submission to the ICME23 conference. We are pleased to inform you that your paper titled ''Free vibration, and static deflections of functionally graded plates using the strain approach and strain-based Reissner–Mindlin elements**"** has been accepted as a full paper for an Oral Presentation by the conference committee of *1st International Congress on Mechanical Engineering – ICME23*.

At least one author of an accepted paper must register (as a full participant) and attend ICME23 for the paper to be included in the proceedings. Furthermore, it is a prerequisite for each paper to have at least one author registered for the conference using the online registration platform accessible at https://forms.gle/HbWrCaoopUQaNDDm9b. If you have already registered, please do not make another registration.

We would like to thank you for your contribution to ICME23 and we are looking forward to seeing you in Constantine, Algeria.

Yours sincerely,

Dr. BENIA Hadj Mohamed
President of the Congress

Pr. BOUCHOUCHA Ali
President of the Congress

Tel: +213(0)31.81.15.60/58 /E-mail: icme23@crm-constantine.dz

We are pleased to have you at the ICME'23. Kindly provide us with details about your keynote presentation and personal information. Please ensure that all information is submitted in English. The communication and registration form should be sent via email to the following address

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Title:
Free vibration, and static deflections of functionally graded plates using the strain approach and strain-based Reissner – Mindlin elements

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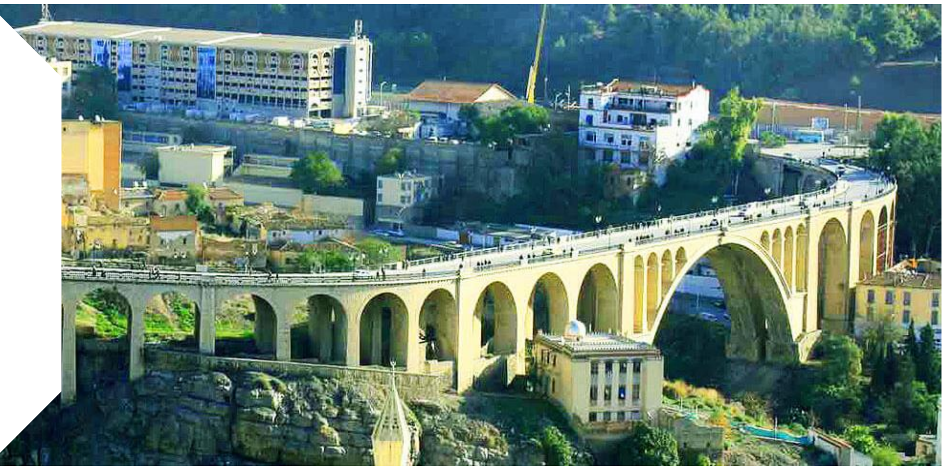
ICME23

FIRST INTERNATIONAL CONGRESS ON MECHANICAL ENGINEERING

CONSTANTINE, ALGERIA
November 15 - 16, 2023



The first International Congress on Mechanical Engineering, ICME'23, is an opportunity to present, discuss, and exchange the results of recent research in the field of mechanics. It aims to be a forum for discussion among researchers and industry professionals. Researchers and doctoral students are invited to share their latest contributions in applied and fundamental research, as well as innovation.

This first edition ICME'23 will take place from November 15th to 16th, 2023, in Constantine. It is jointly organized by the Center of Research in Mechanics (CRM) and the University Constantine 1 (UC1), represented by the Mechanics Laboratory of the Faculty of Science and Technology.
The congress will include presentations by experts and researchers from the international community, oral sessions, and poster presentations. It covers a wide range of topics related to Mechanical Engineering, from design to practical implementation.

Submitted communications can focus on one or more of the listed themes or expand into new areas to ensure broad dissemination of mechanical engineering in other fields.

Accepted contributions will be published in the conference book.
Selected works, after a review process, will be published in an indexed journal.

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TOPICS

1. Design, reverse engineering, and industrialization
2. Advanced manufacturing processes and technologies
3. Optimization of energy mechanical systems and environmental protection
4. Materials and structural damage

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IMPORTANT DATES

September 30, 2023: Deadline proposals submission
October 10, 2023: Notification of Acceptance
October 15, 2023 : Deadline final version
October 31, 2023: Registration end

Registration fees;
Doctoral students: 8 000 DA* / 15 000 DA**; Teachers and researchers: 15 000* /20 000 DA** ; Industrial professionals: 20 000 DA* / 30 000 DA** ; **For participants from abroad**: Doctoral students: 200 Euros; Teachers and researchers: 300 Euros

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Conference Proceedings

"FIRST INTERNATIONAL CONGRESS ON MECHANICAL ENGINEERING"

November 15-16, 2023 Constantine, Algeria

Organized by the Center of Research in Mechanics (CRM)

and

University of Constantine 1 (UC1), Mechanics Laboratory of the Faculty of Science and Technology

Conference Proceedings: “FIRST INTERNATIONAL CONGRESS ON MECHANICAL ENGINEERING”, Constantine, Algeria, 15 - 16. November 2023.

ISBN: 978-9969-9730-0-6

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Preface

The first International Congress on Mechanical Engineering, ICME'23, provides a dynamic platform where we come together to share the latest developments. ICME'23 offers a valuable opportunity for researchers and emerging scholars to exchange knowledge, and explore the ever-evolving frontiers of mechanical engineering.

Scheduled for November 15th to 16th, 2023, in the vibrant city of Constantine, Algeria, ICME'23 is the result of a collaborative effort between the Center of Research in Mechanics (CRM), a young established national research center, and the University Constantine 1 (UC1), represented by the Mechanics Laboratory of the Faculty of Science and Technology. As CRM takes its steps toward further growth and maturity, it plays an essential role in advancing the field of mechanics in Algeria. ICME'23 stands as a proof of our commitment to the continued growth of mechanical engineering research and practice.

ICME'23 is a platform for the exchange of ideas, innovations, and a stage for the presentation of latest research results. International experts, eminent professors and researchers as well as doctoral students were invited to share their contributions, which represent the forefront of applied and fundamental research. The congress offers a unique blend of academic discourse and networking opportunities. It is a space where knowledge transcends boundaries and cultures, and where partnerships and collaborations take root.

The congress is designed to foster knowledge sharing in a variety of formats, including oral presentations and poster sessions. The program encompasses a wide spectrum of Mechanical Engineering themes, ranging from the intricacies of design and reverse engineering to the industrialization of groundbreaking ideas. It extends to the challenges of advanced manufacturing processes and technologies, where the future of mechanical engineering is being forged. Furthermore, it explores the optimization of energy mechanical systems and their profound implications for environmental protection, along with the evolving science of materials and structural damage. These themes are the foundation of modern mechanical engineering, and within them lie the seeds of innovation.

Within these pages, we present the embodiment of research and innovation, and we look forward to the horizons of mechanical engineering.

Welcome to the first International Congress on Mechanical Engineering, ICME'23.

Dr. Hadj Mohamed BENIA
President of ICME’23

Pr. Ali BOUCHOUCHA
President of ICME’23

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Free vibration, and static deflections of functionally graded plates using the strain approach and strain-based Reissner–Mindlin elements

Assas Taqiyeddine [1*], Bourezane Messaoud [1], Chenafi Madjda [1] and Seyfeddine Benabid [2]

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Abstract. In this study, a four-node quadrilateral finite element is presented to study static and free vibration for thick and thin plate bending structures. The strain-based method and the first-order shear deformation theory were used to formulate this element for static and free vibration analyses of the responses of functionally graded (FG) material plates subjected to both sinusoidal and uniformly distributed transversal loads. The material properties of the plate are assumed to be graded continuously in the direction of thickness. The variation of the material properties follows a simple power-law distribution in terms of the volume fractions of the constituents. The suggested element possesses five essential degrees of freedom per node. This element is obtained by the superposition of two strain-based elements, where the first is a membrane with two degrees of freedom per node and the second is a Reissner-Mindlin plate that has three degrees of freedom per node at each of the four corner nodes. Several numerical tests in both static and free vibration analysis are presented to assess the performance of the new element. The results of the present element have proved excellent accuracy and efficiency in predicting bending and free vibration of FG plate.

Keywords: Functionally graded, Strain approach, Finite element

1. Introduction

Functionally graded materials (FGMs) are a type of advanced composite materials usually made from a mixture of ceramics and metals, whose properties vary gradually and continuously from one surface to another. The mechanical properties of FGM vary along the thickness direction in the material depending on a function. Due to this feature, the FGMs have some advantages such as eliminating the material discontinuity and avoiding the delamination failure, reducing the stress levels and deflections. The combination of these characteristics attracts the application of FGMs in many engineering fields from biomedical to civil engineering. With the increased use of these materials for structural components in many engineering applications, the study of static, dynamic, and stability behaviors of these components gains importance among researchers [1]. The FEM was utilized by Praveen and Reddy [2] to examine the static and dynamic thermo-elastic behavior of FG plates. Nguyen-Xuan et al. examined the bending, free vibration, mechanical, and thermal buckling of FG plates using the first-order shear deformation theory (FSDT) [3, 4]. In another research work, Thai and Choi [5] presented a displacement-based finite element model of various unknown shear deformation theories for the bending and free vibration analyses of FG plates with arbitrary boundary conditions. Using his finite element model, Tati [6] examined the buckling behavior of FG plates under mechanical and thermal loadings. Sadgui and Tati [7] formulated a finite element with assumed natural shear strains based on trigonometric shear deformation theory and it was successfully applied for both mechanical buckling and free vibration of FG plates. Two years later, in a different investigation, Belounar et al. [8] created for the first time a novel four-node quadrilateral finite element for static and free vibration responses of functionally graded (FG) material plates based on the strain approach and the first-order shear deformation theory. Each node in the new finite element has five necessary degrees of freedom.

In this article, a new four-node rectangular finite element has been developed using the strain-based approach and the first-order shear deformation theory for static and free vibration analyses responses of functionally graded (FG). The present element named SBRP20 (Strain Based Rectangular Plate with 20 degrees of freedom) has five essential degrees of freedom (u, v, w, βx, βy) at each of the four corner nodes. And their displacement functions are obtained by the superposition of two strain-based elements. The first is a membrane element named SBRIE (Strain-Based Rectangular In-plane Element) [9] with two degrees of freedom (u, v) per node, whereas the second is a Reissner–Mindlin plate element called SBRP (Strain-Based Rectangular Plate) [10] which contains three degrees of freedom (w, βx, βy) per node. The displacement functions of the proposed element contain higher-order terms that satisfy the rigid body modes and they are based on assumed strains satisfying compatibility equations. Several numerical examples using the present element (SBRP20) are presented to demonstrate its performances for FG plates and the obtained results are compared to existing analytical and numerical solutions given in the literature.

2. Materials and Methods

2.1. Functionally Grade Material

In functionally graded materials (FGM), the volume fractions of the material constituents vary continuously across the thickness of the material (Fig. 1).The effective material properties M_{Peff} corresponding to the model of Voigt (Shen, 2009) are evaluated using the relation:

$$M_{Peff} = MP_m V_m(z) + MP_c V_c(z) \quad (1)$$

Where MP_m and MP_c stands for material properties of metals and ceramics respectively. Thus, the modulus of elasticity$E(z)$, and density $\rho(z)$, of FGMs can be given by a simple power law distribution (Simsek, 2009):

$$E(z) = (E_c - E_m)\left(\frac{Z}{h} + \frac{1}{2}\right)^n + E_m \quad (2)$$

$$\rho(z) = (\rho_c - \rho_m)\left(\frac{Z}{h} + \frac{1}{2}\right)^n + \rho_m \quad (3)$$

Where $V_c = V_m = \left(\frac{1}{2} + \frac{z}{h}\right)^n$; $(n \geq 0)$. Poisson's ratio ν is assumed to be a constant through the thickness. Where subscripts c and m indicate the material properties of the ceramic and the metal, respectively, n is the volume fraction exponent, and V_c is the volume fraction of the ceramic (Fig. 2).

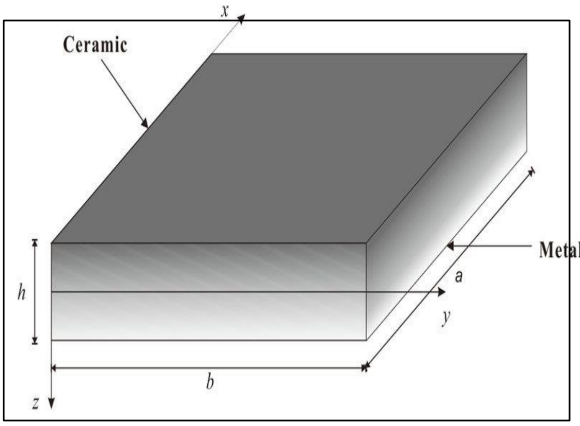

Figure 1: functionally graded (FGM) plate geometry.

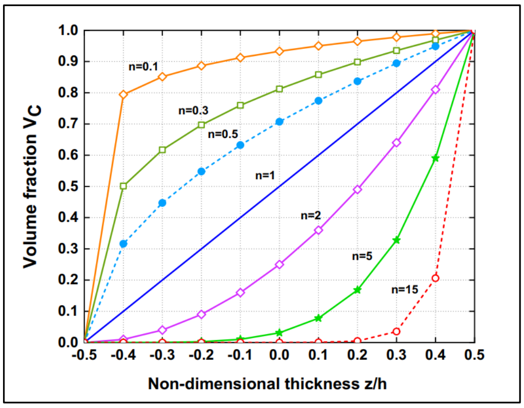

Figure 2: Variation of the volume fraction function against the non-dimensional thickness.

2.2. Finite element formulation

The stiffness matrix of element membrane [$\boldsymbol{K_{SBRIE}}^{\boldsymbol{e}}$]

$$[K_m^e]=\int_{S_e}[B_m]^T\,[D_m][B_m]ds=([C]^{-1})^T\int_{S_e}[Q_m]^T\,[D_m][Q_m]ds[C]^{-1} \quad (4)$$

Where $[B_m] = [Q_m][C]^{-1}$ (5)

In which the membrane strains matrix [Qm] is:

$$[Q_m] = \begin{bmatrix} 0 & 0 & 0 & 1 & Y & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & X & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (6)$$

And the constitutive matrices for membrane $[D_m]$, given by

$$[D_m] = \int_{-h/2}^{h/2}\frac{E(z)}{1-\nu^2}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \left(\frac{1-\nu}{2}\right) \end{bmatrix}dz=\frac{h\widehat{D_a}}{1-\nu^2}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \left(\frac{1-\nu}{2}\right) \end{bmatrix} \quad (7)$$

$$\widehat{D_a} = \int_{-h/2}^{h/2}E(z)dz = \frac{E_c-E_m}{n+1} + E_m \quad (8)$$

The stiffness matrix of element bending [$\boldsymbol{K_{SBRP}}^{\boldsymbol{e}}$]

$$[K_b^e]=\int_{S_e}[B_b]^T\,[D_b][B_b]ds=([C]^{-1})^T\int_{S_e}[Q_b]^T\,[D_b][Q_b]ds[C]^{-1} \quad (9)$$

Where $[B_b] = [Q_b][C]^{-1}$ (10)

In which the membrane strains matrix [Qb] is:

$$[Q_b] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & Y & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & X & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (11)$$

And the constitutive matrices for bending [Db], given by

$$[D_b] = \int_{-h/2}^{h/2}\frac{E(z)}{1-\nu^2}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \left(\frac{1-\nu}{2}\right) \end{bmatrix}(z)^2dz=\frac{h^3\widehat{D_b}}{1-\nu^2}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \left(\frac{1-\nu}{2}\right) \end{bmatrix} \quad (12)$$

$$\widehat{\mathrm{D_b}} = \int_{-\mathrm{h}/2}^{\mathrm{h}/2}\mathrm{E(z)(z)^2dz} \quad (13)$$

The stiffness matrix of element shear [$\boldsymbol{K_S}^{\boldsymbol{e}}$]

$$[K_s^e] = \int_{S_e}[B_s]^T\,[D_s][B_s]ds = ([C]^{-1})^T\int_{S_e}[B_s]^T\,[D_s][B_s]ds[C]^{-1} \quad (14)$$

Where $[B_s] = [Q_s][C]^{-1}$ (15)

In which the membrane strains matrix [Qs] is:

$$[\mathrm{Q_s}] = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & (-\mathrm{Y}^2) & 0 & 1 & \mathrm{Y} & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & (-\mathrm{X}^2) & 0 & 0 & 0 & 0 & 0 & 1 & \mathrm{X} \end{bmatrix} \quad (16)$$

$$[\mathrm{D_s}] = \int_{-\mathrm{h}/2}^{\mathrm{h}/2}\frac{\mu\,\mathrm{E(z)}}{2(1+\nu)}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}\mathrm{dz}=\frac{\mu\,\mathrm{h}\,\widehat{\mathrm{D_s}}}{2(1+\nu)}\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (17)$$

$$\widehat{\mathrm{D_s}}=\int_{-\mathrm{h}/2}^{\mathrm{h}/2}\mathrm{E(z)dz} = \frac{\mathrm{E_c-E_m}}{\mathrm{n+1}} + \mathrm{E_m} \quad (18)$$

The stiffness matrix of the coupled membrane-bending [$\boldsymbol{K_{SBRIE-SBRP}}^{\boldsymbol{e}}$]

$$[K_{mb}^e] = \int_{S_e}[B_{mb}]^T\,[D_{ab}][B_{mb}]ds = ([C]^{-1})^T\int_{S_e}[Q_m]^T\,[D_{ab}][Q_b]ds[C]^{-1} \quad (19)$$

$$[\mathrm{D_{ab}}] = \int_{-\mathrm{h}/2}^{\mathrm{h}/2}\frac{h^2\,\widehat{D_{ab}}}{(1-\nu^2)}\begin{bmatrix} 1 & \nu & 0 \\ \nu & 1 & 0 \\ 0 & 0 & \left(\frac{1-\nu}{2}\right) \end{bmatrix}\mathrm{dz} \quad (20)$$

$$\widehat{D_{ab}}=\int_{-h/2}^{h/2} zE(z)dz = \frac{n}{(n+2)(n+1)}(E_c - E_m) \tag{21}$$

The element stiffness matrix $[K^e]$ is composed of the summation of five matrices as:

$$[K^e] = [K_m^e] + [K_b^e] + [K_c^e] + [K_{mb}^e] + [K_{bm}^e] \tag{22}$$

The element mass matrix $[M^e]$ can be computed by the following equation:

$$[M^e] = \int_{S_e}[N]^T[m]\,[N]dS=[C^{-1}]^T\left(\int_{S_e}([P]^T[m][P])dxdy\right)[C^{-1}] \tag{23}$$

$$\text{Where } [P] = \begin{bmatrix} [P_m] & [0]_{2,12} \\ [0]_{3,8} & [P_b] \end{bmatrix} \text{ and } [C] = \{[P1]\ [P2]\ [P3]\ [P4]\}^T \tag{24}$$

For a matrix $[P_m]$ *and* $[P_b]$ see appendix in reference [9], [10]

For free vibration, the mass matrix [m] which contains the mass density ρ varying in z direction can be given as

$$[m]=\begin{bmatrix} I_0 & 0 & 0 & I_1 & 0 \\ 0 & I_0 & 0 & 0 & I_1 \\ 0 & 0 & I_0 & 0 & 0 \\ I_1 & 0 & 0 & I_2 & 0 \\ 0 & I_1 & 0 & 0 & I_2 \end{bmatrix} \tag{25}$$

where $$(I_0, I_1, I_2)=\int_{-\frac{h}{2}}^{\frac{h}{2}} \rho(z)\,(1, z, z^2)dz \tag{26}$$

For static and free vibration analysis, the formulations can be, respectively, written:

$$[K^e]\{q_e\} = \{F^e\} \tag{27}$$

$$[K^e] - \omega^2[M^e] = 0 \tag{28}$$

Where ω is the natural frequency

3. Results and discussion

3.1. Static behavior analysis

Square plates under uniform

In order to demonstrate the viability of the suggested finite element formulation in forecasting the static bending and free vibration responses of FG plates, various numerical examples are shown and analyzed in this section. Table 1 lists the material parameters of the several FG plates that are taken into consideration. The following dimensionless forms are utilized for convenience:

$$\overline{W} = \frac{100\times w_c\times E_m\times h^3}{12\times q_0\times a^4\times(1-\nu^2)} \tag{29}$$

Table 1: Mechanical properties of the material used in functionally graded material

Properties	**Metal**	**Ceramic**	
	Aluminum (Al)	Zirconia (ZrO_2-2)	Alumina (Al_2O_3)
E(Gpa)	70	200	380
ϑ	0.3	0.3	0.3
ρ(kg/m^3)	2707	5700	3800

Example 1 An Al/ZrO2 square plate with simply supported (SSSS) and clamped (CCCC) boundary conditions is used as an example. The non-dimensional central displacement $\overline{W}$ is calculated using the current formulation, and it is compared with other approaches available in the literature [4, 8, 12–15] and a very good agreement can be observed. Table 2 displays the findings for various power-law index n and side-to-thickness ratio a/h =5. It is evident that the current results and the cited references are well-concordant. They are nevertheless getting nearer to MITC4 [4] fixes

Table 2: Dimensionless deflection ($\overline{W}$) of Al/ZrO2 square plates under uniform loads with (a/h = 5)

boundary condition	Methods	n=0	n=0.5	n=1	n=2
SSSS	SBRP20(8x8)	0.1643	0.2224	0.2601	0.2988
	SBRP20(12x12)	0.1684	0.2280	0.2667	0.3056
	SBRP20(16x16)	0.1698	0.2299	0.2690	0.3082
	SBRP20(20x20)	0.1705	0.2308	0.2710	0.3098
	SBQP20 [8]	0.1714	0.2321	0.2716	0.3111
	IGA-Quadratic [12]	0.1717	0.2324	0.2719	0.3115
	MITC4 [4]	0.1715	0.2317	0.2704	0.3093
	ES-DSG3 [13, 4]	0.1700	0.2296	0.2680	0.3066
	NS-DSG3 [4]	0.1721	0.2326	0.2716	0.3107
	kip-Ritz [14]	0.1722	0.2403	0.2811	0.3221
	MLPG [15]	0.1671	0.2505	0.2905	0.3280
CCCC	SBRP20(8x8)	0.0730	0.0965	0.1130	0.1306
	SBRP20(12x12)	0.0748	0.0995	0.1160	0.1341
	SBRP20(16x16)	0.0752	0.1005	0.1172	0.1355
	SBRP20(20x20)	0.0756	0.1010	0.1179	0.1364
	SBQP20 [8]	0.0759	0.1011	0.1180	0.1366
	IGA-Quadratic [12]	0.0760	0.1013	0.1183	0.1369
	MITC4 [4]	0.0758	0.1010	0.1179	0.1365
	ES-DSG3 [13, 4]	0.0761	0.1013	0.1183	0.1370
	NS-DSG3 [4]	0.0788	0.1051	0.1227	0.1420
	kip-Ritz [14]	0.0774	0.1034	0.1207	0.1404
	MLPG [15]	0.0731	0.1073	0.1253	0.1444

3.2. Free vibration analysis

Square plates

In this part, the free vibration responses of different FG plates have been examined using the current finite element formulation. The following dimensionless forms are utilized for convenience

$$\overline{\beta}=\omega h\sqrt{\frac{\rho_m}{E_m}} \tag{30}$$

Example 01

The stability of the suggested rectangular element is examined using the convergence tests of fully simply supported Al/Al2O3 square plates with three thickness-to-side ratios (a/h = 5, 10 and 20) and various values of the volume fraction exponent (n). The resultat presented in Table 3 and compared with other approaches available in the literature [15–19]. In general, a good agreement between the results is found. It can be observed that the solutions from this formulation are very close to those reported by Quazi-3D [19] for all FG plates with various values of power-law index p. additionally, it is demonstrated in Table 3 that the fundamental natural frequency $\bar{\beta}$ decreases for all cases when the volume fraction exponent n increases. This is due to a change in plate rigidity that is connected to the properties of the materials.

Table 3: The influence of thickness ratio (a/h), volume fraction index (n), on dimensionless frequency ($\overline{\beta}$) of SSSS Al/Al_2O_3 square plate

a/h	Theory	Power-law index p			
		P=0	P=1	P=2	P=5
10	3D [18]	0.1135	0.0870	0.0789	0.0741
	HSDT [16]	0.1134	0.0868	0.0788	0.0740
	Quazi-3D [19]	0.1137	0.0883	0.0807	0.0756
	Sadgui and Tati [17]	0.1136	0.0870	0.0788	0.0738
	SBRP24 (8×8)	0.1153	0.0883	0.0802	0.0756
	SBRP24 (12×12)	0.1142	0.0874	0.0794	0.0749
	SBRP24 (16×16)	0.1139	0.0872	0.0792	0.0747
	SBRP24 (20×20)	0.1137	0.0870	0.0790	0.0746
5	3D [18]	0.4169	0.3222	0.2905	0.2676
	HSDT [16]	0.4151	0.3205	0.2892	0.2666
	Quazi-3D [19]	0.4178	0.3267	0.2968	0.2725
	Sadgui and Tati [17]	0.4156	0.3210	0.2883	0.2632
	SBRP24 (8×8)	0.4214	0.3254	0.2949	0.2751
	SBRP24 (12×12)	0.4180	0.3227	0.2924	0.2728
	SBRP24 (16×16)	0.4168	0.3217	0.2915	0.2721
	SBRP24 (20×20)	0.4163	0.3213	0.2911	0.2717
2	3D [18]	1.8470	1.4687	1.3095	1.1450
	HSDT [16]	1.8277	1.4460	1.2896	1.1312
	Quazi-3D [19]	1.8583	1.4830	1.3269	1.1576
	Sadgui and Tati [17]	1.8224	1.4435	1.2675	1.0829
	SBRP24 (8×8)	1.8425	1.4586	1.3152	1.1910
	SBRP24 (12×12)	1.8310	1.4490	1.3065	1.1834
	SBRP24 (16×16)	1.8270	1.4457	1.3035	1.1808
	SBRP24 (20×20)	1.8252	1.4442	1.3021	1.1796

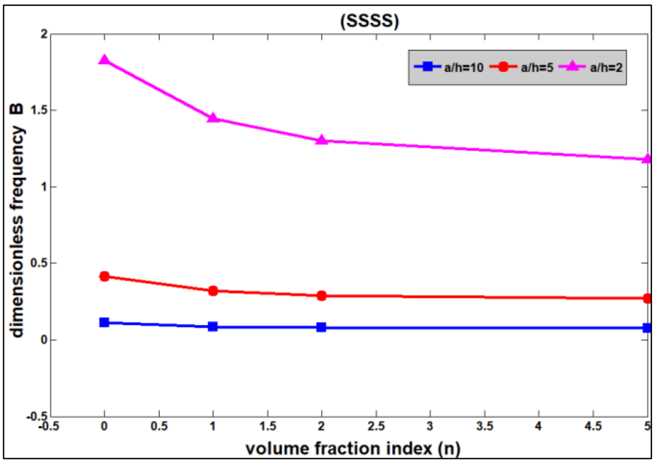

Figure 2: The effect of volume fraction index (n) on dimensionless frequency ($\overline{\beta}$) of square plate with different thickness ratio (a/h)

4. Conclusion

This work introduces a novel four-node quadrilateral finite element based on the strain approach and the first-order shear deformation theory for static and free vibration responses of functionally graded (FG) material plates. This element named SBRP20 has five essential degrees of freedom at each of the four corner nodes. The performance and viability of the SBRP20 element have been demonstrated through several numerical applications for static and free vibration of FG plates with various boundary conditions, side-to-thickness ratios, and several values of gradient index n. The obtained results of the SBRP20 element have been found to agree globally well with published reference solutions for both static and free vibration problems. In perspective, this element can be further extended for the analysis of FG plates subjected to thermal loads and mechanical/thermal buckling as well as FG shell structures.

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