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Numerical Modeling of Coupled Thermo-Mechanical Bending Response in Functionally Graded Material Sandwich Beams

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ABSTRACT

This study presents a novel comprehensive numerical investigation of the mechanical and thermo-mechanical behavior of FGM beams using Nonlinear Finite Element Analysis (NLFEA) implemented under ABAQUS. The studied beam is a rectangular-type sandwich beam with a polymer (PVC) foam core and polypropylene (PP) facings. Numerical FEM were firstly validated using experimental data from the literature and secondly extended to investigate additional loading and thermal conditions. The main objective is to assess the influence of the material gradient index (p) and the number of layers used for material discretization on stress distribution, stiffness, and ductility. Results in terms load-capacity curves and deformation patterns indicate that the gradient index strongly affects the overall beam response. While, the beam layers' layout influences the stress redistribution along the thickness, with finer discretization producing smoother transitions. Comparing purely mechanical and thermo-mechanical loading, it is observed that thermal gradients introduce additional stresses due to differential expansion, altering the global stress field and interacting with the material gradation.

1 Introduction

Functionally graded materials (FGMs) are innovative composites made from a heterogeneous mixture of two or more constituents [1–4]. Currently, the concept of FGM is commonly relevant in several fields, including aerospace, energy conversion, civil engineering and biosystems [5]. Such materials are characterized by a continuously and smoothly varying

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microstructure and composition, designed to enhance the mechanical and thermal performance of the structural components[6, 7]. Beyond their historical development and wide range of applications, (FGMs) have actually involved the consideration of researchers regarding their behavior under both mechanical and thermal loadings. Compared to conventional composite materials susceptible to debonding, functionally graded composites exhibit improved resistance to damage [8]. Indeed, FGMs were originally developed for thermal applications in spacecraft projects[9]. In this respect, Sina and al. [10] established a novel beam theory to investigate the dynamic response of functionally graded beams. While, Lee and al. [11] used an exact transfer matrix expression. In addition, rotating beams[12], dynamics of microplates [13], porous microstructures with thermo-mechanical properties [14], and buckling [15] have been investigated.

While numerous investigations have explored the mechanical and thermal characteristics of FGMs, few studies have addressed the combined nonlinear thermomechanical behavior of FGM beams under bending. However, several studies have analyzed the thermoelastic behavior of FGMs under different thermal and mechanical loadings, For instance, Simonetti and al. [16]focuses on the thermo-mechanical stability of open functionally graded beam-type structures under combined thermal and mechanical loading. A nonlinear finite-element beam formulation is developed that accounts for various temperature distributions through the wall height and temperature-dependent material properties. Moreover, Szlachetka et al. [17] have analyzed the influence of layer gradation and abrupt transitions on stress distributions using tolerance modeling and FEMs. Alqahtani et al. [18] have presented a generalized thermoelastic analysis of graded materials solicited by a timed pulse laser source. Using a generalized thermoelastic theory with a single relaxation time, the authors establish coupled governing equations that describe heat conduction and elastic responses in graded materials.

In the same perspective with investigations dedicated on FGM beams, several studies have focused on sandwich structures with functionally graded cores. In this context, Arslan and Gunes [19] presented an experimental study which consists in determining the dynamic response of honeycomb composite members with FGM faceplates. In addition, Wu and al. [20] conducted an experimental and numerical study of the static and fatigue behavior of the composite honeycomb sandwich structure with skins made of composite resins reinforced with carbon fiber hexagonal cell structure. In addition, Medjmadj et al. [21]explored the conception and combined physical and thermal testing of plaster/cork functionally graded core sandwich structures made of polymer face sheets and epoxy resin adhesive layer. Moreover, numerical modeling with powerful means for the study of complex mechanical phenomena of sandwich panels have been currently focused[22]. Furthermore, Bahabadi, et al. [23] have experimentally and numerically investigated the behavior of corrugated core filled with PVC foam beams under flexural loading to assess the skin-core resistance to separation.

Although significant growth has been achieved in understanding the mechanical and thermal behavior of functionally graded materials, limited attention has been devoted to a systematic and comparative investigation of mechanical bending and coupled thermo-mechanical nonlinear responses of FGM beams. Accordingly, the originality of the present work is to establish validated FEM models able to simulate the post-elastic behavior of sandwich beams. Subsequently, a comprehensive thermo-mechanical analysis is performed using the finite element software ABAQUS [24] in order to evaluate the coupled effects of temperature gradients and mechanical bending. Particular attention is devoted to the interaction between material gradation and thermal distribution across the beam thickness, and to their combined impact on stress evolution and global deformation patterns. Finally, the numerical findings are systematically compared with available theoretical models to ensure consistency and to provide deeper insight into the role of material gradation under both mechanical and thermo-mechanical loading conditions.

2 Problem statement and description

Experimental investigations on functionally graded material (FGM) beams remain limited and realistically demanding [25], particularly when combined thermo-mechanical loading and plasticity effects are considered [26]. The manufacturing complexity of graded materials, the control of material gradients, and the difficulty of accurately measuring temperature-dependent inelastic responses make such tests delicate and costly [27] .Consequently, most available studies addressing thermo-mechanical behavior, plasticity, and parametric analyses of FGM beams are predominantly analytical or purely numerical [28–30]. Although some works have reported combined experimental–numerical bending investigations on porous or nanoparticle-reinforced FGMs [31], these contributions are generally restricted to specific material configurations and do not provide a comprehensive experimental validation framework under coupled thermo-mechanical conditions with plastic deformation.

To overcome this lack of experimental validation, a benchmark strategy was adopted. An experimental study on a non-FGM sandwich beam with well-documented reference test data was first selected as a validation case. A detailed finite element model was then developed using ABAQUS [24] and calibrated to accurately reproduce the measured mechanical response. Once validated, the numerical framework was extended to a sandwich beam incorporating an FGM core. This approach enabled the investigation of thermo-mechanical bending behavior while explicitly accounting for plasticity effects, followed by systematic parametric analyses. In this way, the validated reference configuration ensures the robustness and credibility of the extended simulations on the FGM system.

3 FEM procedure

A full three-dimensional nonlinear finite element model was developed to accurately account for the real mechanical behavior of the constituent materials as well as the geometric characteristics of the sandwich beam. The reference sandwich beam configuration was originally designed and experimentally tested under bending until failure by Bahabadi et al. [23], which investigated several core densities. The principal objective of the present work is to establish a validated numerical framework based on these experimental results before extending the analysis to a functionally graded (FGM) core configuration. In this context, the different core densities investigated by Bahabadi et al. [23]are incorporated into the same geometric configuration but reformulated within a functionally graded degradation profile, allowing a continuous variation of material properties through the core thickness. Consequently, this section introduces the numerical modeling strategy, including material constitutive laws, geometric modeling and boundary conditions.

3.1 Geometric implementation

This section describes the geometrical modeling and numerical setup of the sandwich beam. The core is modeled using 3D solid elements to capture the through-thickness stress state, while the face sheets are modeled with shell elements to efficiently represent their thin structural behavior. The three parts are created separately and assembled concentrically. The FGM beam dimensions are: total thickness $H=15$ *mm*, length $L=370$ mm and width $b=60$ *mm*. Each face sheet (skin) has a thickness of *1 mm*, while the remaining thickness corresponds to the graded core. Figure 1 illustrates the generated 3D sandwich beam model, including the solid core and the shell face sheets after assembly.

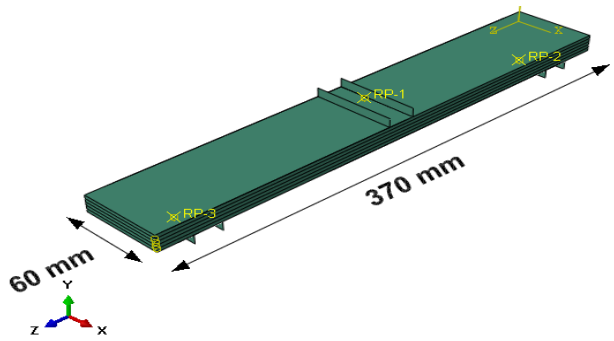


Fig. 1- 3D modelling of the FGM beams.

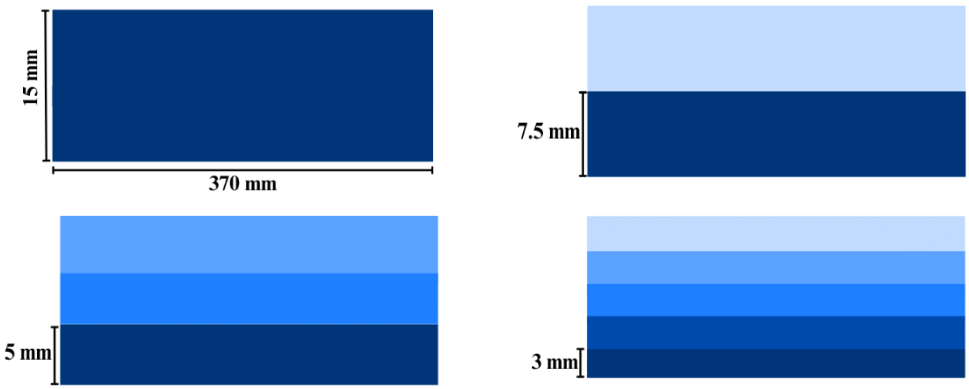


Fig. 2- Considered and simulated FGM Core layouts.

The analysis is carried out using a Dynamic Explicit step with a coupled temperature–displacement formulation in ABAQUS[24]. Although the loading corresponds to quasi-static bending, the explicit formulation is adopted to confirm numerical reliability regarding the material nonlinearities. Figure 2 presents the three considered FGM core configurations, defined according to the through-thickness discretization into layers, where each layer is assigned distinct material properties to represent the functional gradation.

3.2 Materials modeling

To simulate the actual response of the functionally graded beam, a finite element model with an elastoplastic material formulation is employed for the PVC foam core. Two density cases were considered: *60 kg/m³* and *200 kg/m³*, corresponding to the bottom and top surfaces of the FGM beam, respectively. Table 1 summarizes the material parameters associated with each foam. Furthermore, the variation of material properties $E(z)$ through the core thickness is modeled using the FGM power-law distribution defined in Eq. (1), which governs the gradation of each parameter along the core height. Table 1 also presents an example of the homogenized properties obtained for a representative FGM configuration.

$$X_i(y) = X_{i1} + \left(\frac{y}{h} + \frac{1}{2}\right)^p (X_{i2} - X_{i1}) \quad (1)$$

In which X_1 represents material parameter corresponding to the bottom beam face with a rigidity of 45 MPa, X_2 represents material parameter corresponding to the top beam face a rigidity of 175 MPa. The position *y* is the distance between the centroid of a given layer and the centroid of the entire core. *p* is the index of the power-law function governing the gradation.

Table 1 - Main proprieties of used PVC foam[23]

Denotation	Symbol (Units)	Values		
		$\boldsymbol{X_{i1}}$ [23]	$\boldsymbol{X_{i2}}$[23]	$\boldsymbol{X_i\ (y = 0.5)}$ **and p=0.1**
Real density	D (kg/m³)	175	45	52.73
Thermal conductivity	C (W /m. K)	0.034	0.048	0.0741
Coefficient of thermal dilatation	α (µm/m°C)	60	80	78.78
Young modulus	E (MPa)	200	60	68.53
Poisson' ratio	υ	0.3	0.3	0.3
Yield stress	σ_e(Mpa)	1.20	0.55	0.59
Ultimate stress	σ_u(Mpa)	2.20	1.1	1.16

The composite PP facings were modeled assuming a linear elastic orthotropic behavior throughout the analysis. The in-plane young's moduli are E_{xx} and E_{yy} =13.7GPa, while the transverse modulus is E_{zz}=1.02GPa. The shear moduli are G_{xy} and G_{xz}=1.7 GPa. However, the moduli G_{yz}=1.6 GPa, with corresponding Poisson's ratios ϑ_{xy} and ϑ_{xz}=0.3, and ϑ_{yz}=0.21. According to Bahabadi et al. [23], no plasticity or damage evolution laws were considered for the face sheets, as they were assumed to remain within the elastic range under the applied loading conditions.

3.3 FEM and Boundary conditions

The graded material core is meshed with eight-node hexahedral solid elements employing reduced numerical integration (ABAQUS element type C3D8R), following the modeling strategy reported in [32]. The top and bottom polypropylene face layers are represented by four-node quadrilateral shell elements with reduced integration and finite membrane strain capability (S4R), as recommended in [33]. In addition, an interaction formulation based on surface-to-surface contact is implemented to describe the mechanical interaction between the loading indenter and the upper face sheet. Normal hard contact behavior is adopted. However, perfect bonding between the solid core and the shell skins is ensured using surface-based tie constraints. A three-point bending mechanical load is applied to the FGM beam. The loading is monotonic, gradually increasing until failure for a complete evaluation and to ensure quasi-static conditions while maintaining numerical stability.

While, the thermal load is applied to the studied FGM beam as follows: An initial uniform temperature of 10 °C is imposed throughout the whole beam-section. The temperature is then monotonically increased in increments of 10 °C and the maximum final temperature applied to the beam is 100 °C. This procedure allows simulating the effect of progressive heating on the thermo-mechanical behavior of the beam and enables the analysis of stress redistribution and deformation induced by the thermal gradient.

4 Results and discussions

To demonstrate the predictive capability of the developed model, this section is structured in three main stages. First, the non-FGM sandwich beam is validated under three-point bending by comparing the numerical and experimental load–displacement curves, stiffness and ultimate load to experimental data. Second, the results of the extended model to the FGM core by introducing a power-law material gradation are highlighted. The influence of the power-law index and the number of discretized layers is focused through load–displacement responses and stress cartographies. Finally, the numerical outcomes under coupled thermo-mechanical loading are presented, showing the combined influence of thermal effects and material gradation on the global structural response and stress localization within the beam.

4.1 FEM validation of Non-FGM beams

To assess the accuracy of the established simulations, a quantitative comparison of FEM outcomes with experimental data reported in the literature [23]was conducted . Indeed, Figure 3 presents the force–displacement curves, showing a satisfactory correlation between the numerical and experimental results in terms of the overall flexural behavior of the beam. The discrepancy of the FEM and test values is below 5 %, which is well less than the suitable experimental deviation. The maximum load predicted by the FEM model is *582.9 N*, while Bahabadi et al. [23] reported an experimental maximum load of approximately *590 N*.

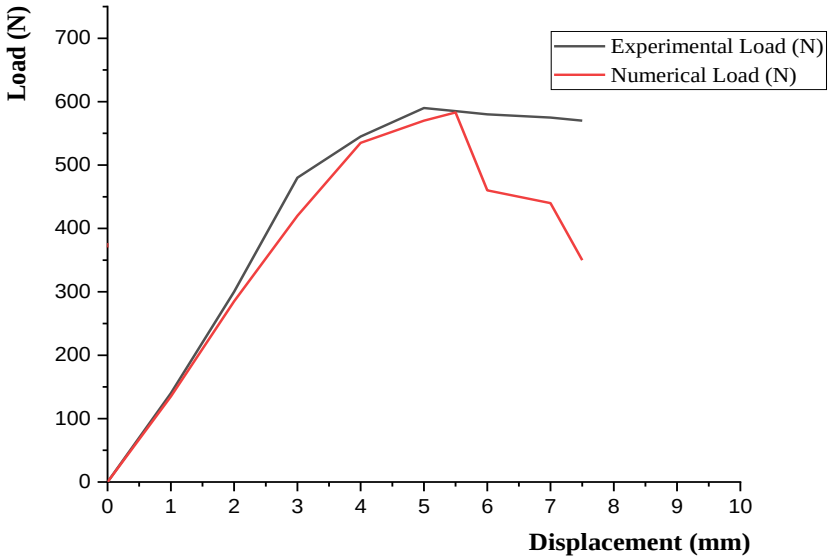
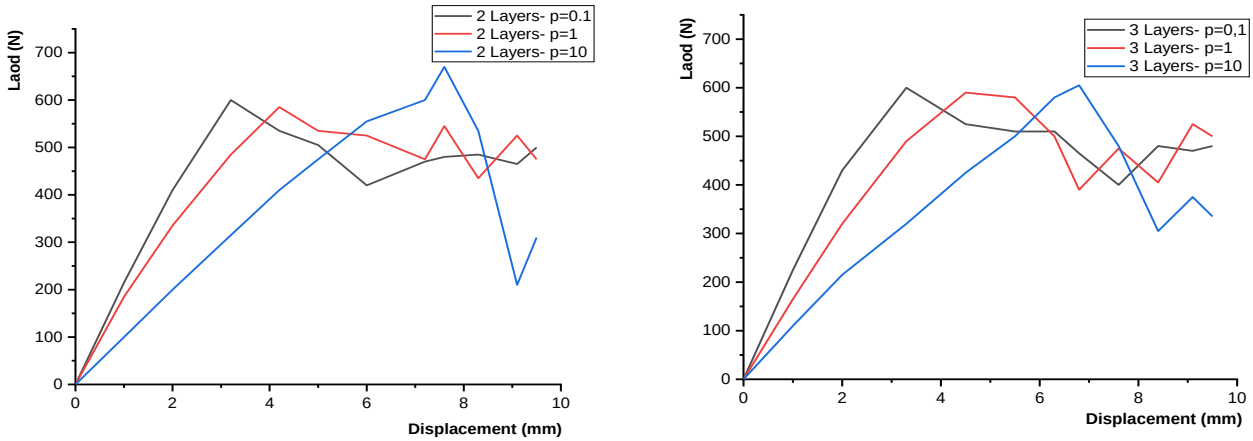


Fig. 3 - Force–displacement curves comparing the FEM model predictions with the experimental data [23].

The initial linear phase of both curves reflects the global elastic stiffness of the sandwich beam, mainly governed by the bending rigidity, where the polypropylene skins carry most of the tensile and compressive stresses while the PVC foam core ensures shear transfer and stabilizes the facings against local buckling. As loading increases, both curves reach a peak around *5 mm* displacement, corresponding to the onset of damage mechanisms. Physically, this stage is associated with core shear cracking, local crushing of the foam beneath the loading point, and initiation of interfacial debonding. The experimental curve shows a smoother post-peak softening, indicating progressive damage evolution and stable crack propagation, which enhances energy dissipation and global ductility. In contrast, the numerical curve exhibits a more pronounced load drop after the peak. Numerically, this can be attributed to the local failure criteria of stiffness degradation and excessive damage, leading to a rapid loss of load-carrying capacity.

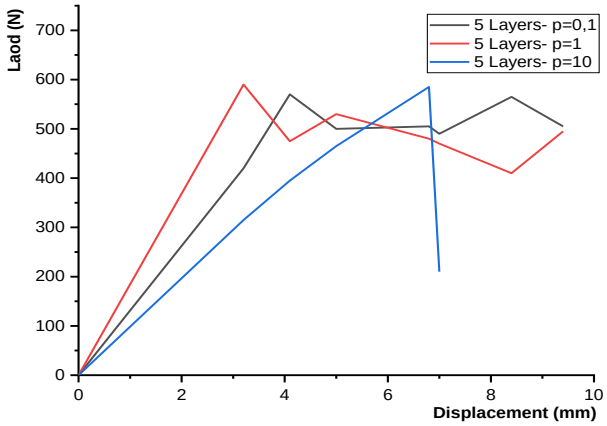
4.2 FGM Beams under mechanical loading

Figure 4 shows the confrontation of the load–mid-span displacement curves for all simulations, illustrating the effect of the gradient index *p* of the FGM core material and the number of discretized layers on the flexural response. The outcomes demonstrate that growing the number of layers allows to achieve additional representation of the continuous material gradation and affects the peak load and deformation characteristics.



a)

b)



c)

Fig. 4 - The load–displacement bending responses according to power law FGM index: a) 2-descrtized layers; b) 3-descrtized layers; c) 5-descrtized layers.

The load–displacement responses indicate that the flexural rigidity, increases with the number of FGM layers due to a smoother through-thickness material gradation and improved stress transfer between constituents. The initial linear phase confirms higher global stiffness for 3 and 5 layer configurations compared to the 2-layer beam, where stiffness discontinuities promote premature local softening. In terms of resistance, the peak load is maximized for moderate gradation ($p = 1$), reflecting a balanced distribution between stiff and compliant phases, which optimizes the section modulus and delays core yielding. For higher power-law indices ($p = 10$), the stiffness becomes more core-dominated and less efficiently distributed, slightly reducing ultimate capacity. Regarding ductility, multilayer configurations exhibit a more stable post-peak regime with gradual stiffness degradation, indicating progressive damage evolution and reduced stress concentration effects. Physically, increasing the number of layers enhances interlaminar compatibility, mitigates abrupt modulus jumps and promotes distributed plasticity, thereby improving both structural stability and energy absorption capacity.

For further illustration, stress contours showing the progressive evolution of stresses in the FGM beams under bending, highlighting the transition from the onset of plastic deformation to the fully developed plastic state, for a unit gradient parameter are provided in Figure 5.

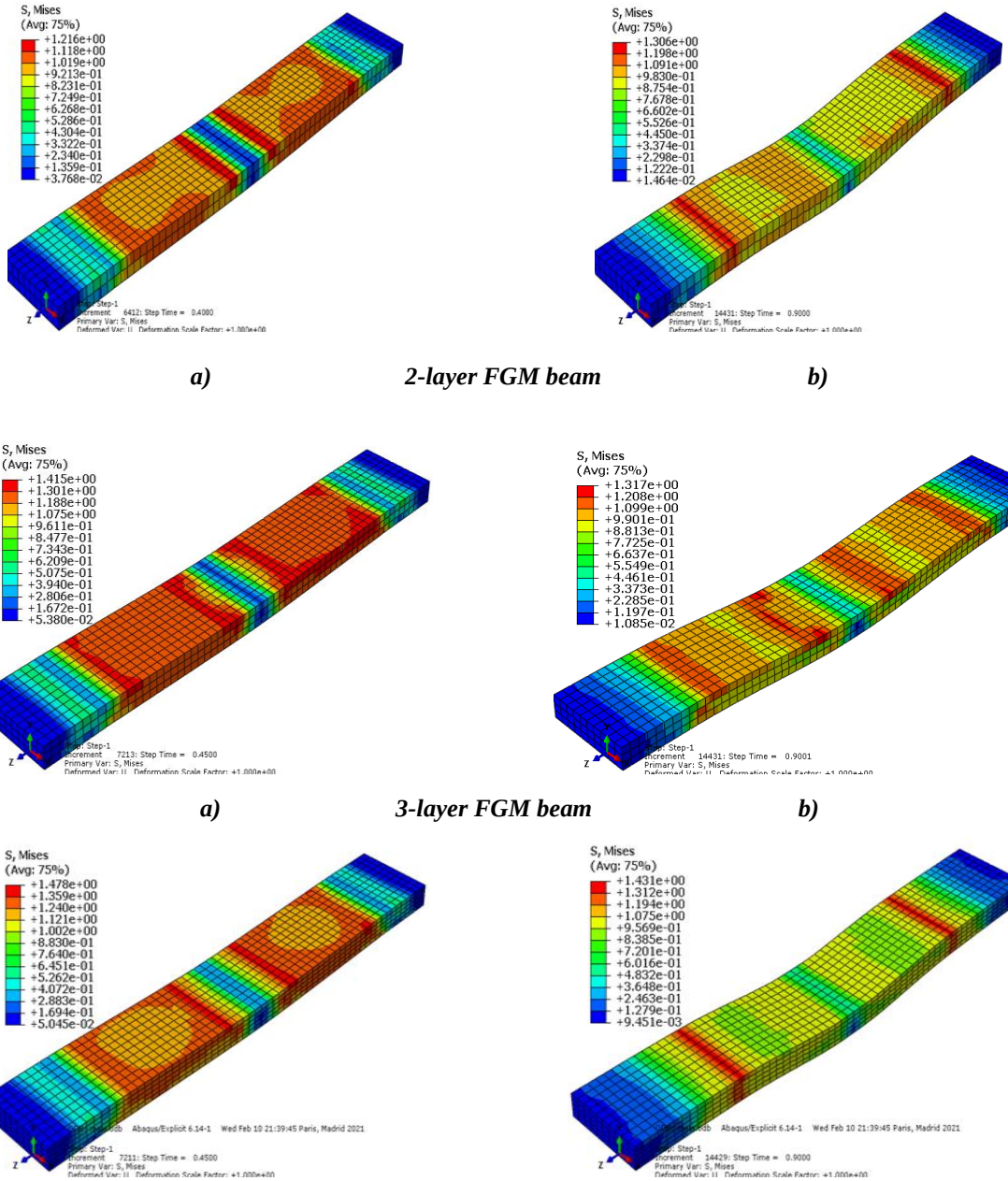


Fig. 5 - Stress contours in the unit gradient parameter FGM beams under bending: a) Onset of plastic deformation; b) Fully developed plastic state.

At the onset of plastic deformation, the stress field reflects the initial yielding of the most highly stressed zones under bending. Plasticity first develops at the upper skin–core interface directly below the loading point, where compressive stresses reach the yield limit, and then extends gradually toward the support regions following the bending moment distribution. For the 2-layer configuration, the stiffness divergence between layers induces a steeper stress gradient through the thickness, promoting faster stress propagation and earlier local yielding. In contrast, the 3-layer and 5-layer configurations exhibit a smoother stress transition, which delays the spread of plasticity. The maximum stresses at this stage are approximately 1.2 MPa (2 layers), 1.4 MPa (3 layers), and 1.47 MPa (5 layers). The slightly higher stress levels observed for finer discretization indicate improved load transfer efficiency and enhanced structural resistance before extensive plastic flow develops.

However, at a load increment corresponding to the fully developed plastic state, the plastic zone becomes well established and extends significantly within the core loading region. The stress contours reveal pronounced localization near the loading point and secondary concentrations close to the supports, consistent with maximum bending moment and shear effects. In the 2-layer beam, plastic deformation spreads more abruptly due to the limited gradation, resulting in sharper stress concentrations and reduced redistribution capacity. Conversely, the 3-layer and especially the 5-layer configurations demonstrate a more progressive redistribution of stresses through the thickness, reflecting enhanced ductility and energy dissipation capacity. The finer gradation mitigates abrupt stiffness discontinuities, allowing smoother stress diffusion and delaying the formation of critical localized failure zones under advanced plastic deformation.

4.3 FGM Beams under thermomechanical loading

Figure 6 displays the load–displacement curves of FGM beams subjected to thermomechanical loading, with an initial temperature of 10 °C and temperature increments of 10 °C up to 100 °C. These results allow assessing the combined effect of bending and thermal gradient on the mechanical response of FGM beams. The same procedure applied for the purely mechanical loading was used for thermomechanical loading. The gradient parameter p was investigated for three values: 0.1, 1, and 10, while keeping the same number of layers for each curve. This analysis allows assessing the influence of the rate of material property variation on the flexural–thermal response of FGM beams.

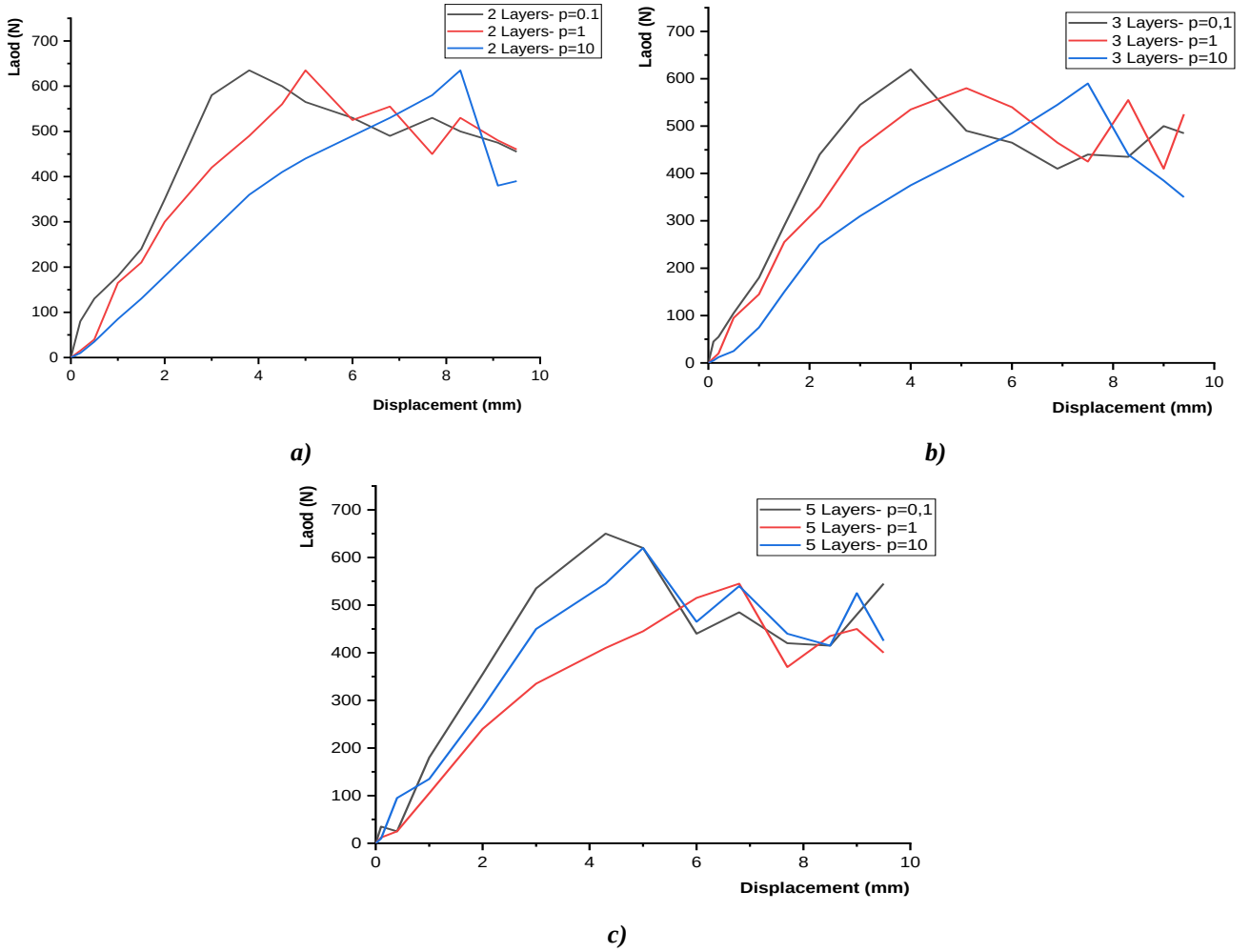


Fig. 6 - Load–displacement thermomechanical responses according to power law FGM index: a) 2-descrtized layers; b) 3-descrtized layers; c) 5-descrtized layers.

Under thermo-mechanical loading, the load–displacement response exhibits a noticeable reduction in global stiffness and peak load compared to the purely mechanical case, due to thermal softening of the core material and the development of additional thermal stresses through the thickness. Elevated thermal conditions result in a decline in the material's rigidity and accelerate plastic yielding, leading to earlier deviation from linearity and a more pronounced post-peak degradation.

The influence of the power-law index p becomes more significant: low p values (stiffer material concentrated near the faces) show higher initial rigidity but experience sharper load drops, indicating thermal–mechanical stress concentration and earlier local instability. In contrast, higher p values promote a more gradual stiffness distribution across the thickness, which improves stress redistribution under combined bending and thermal expansion, resulting in a smoother softening branch and relatively enhanced ductility. Increasing the number of layers from 2 to 5 reduces sudden load fluctuations, reflecting better continuity of thermo-elastic properties and mitigation of interlayer stress disparity. Overall, the thermo-mechanical coupling amplifies material heterogeneity effects, making graded configurations with refined layering more stable and damage-tolerant under combined loading.

However, closer examination of the deformation behavior suggests a subtle influence on ductility: beams with 5 layers begin to deform at slightly lower loads, implying a reduction in ductility as the number of layers' increases. Consequently, a higher number of layers results in a slightly more brittle response and a more abrupt failure mode. In this respect, the localization of stresses is provided in Figure 7.

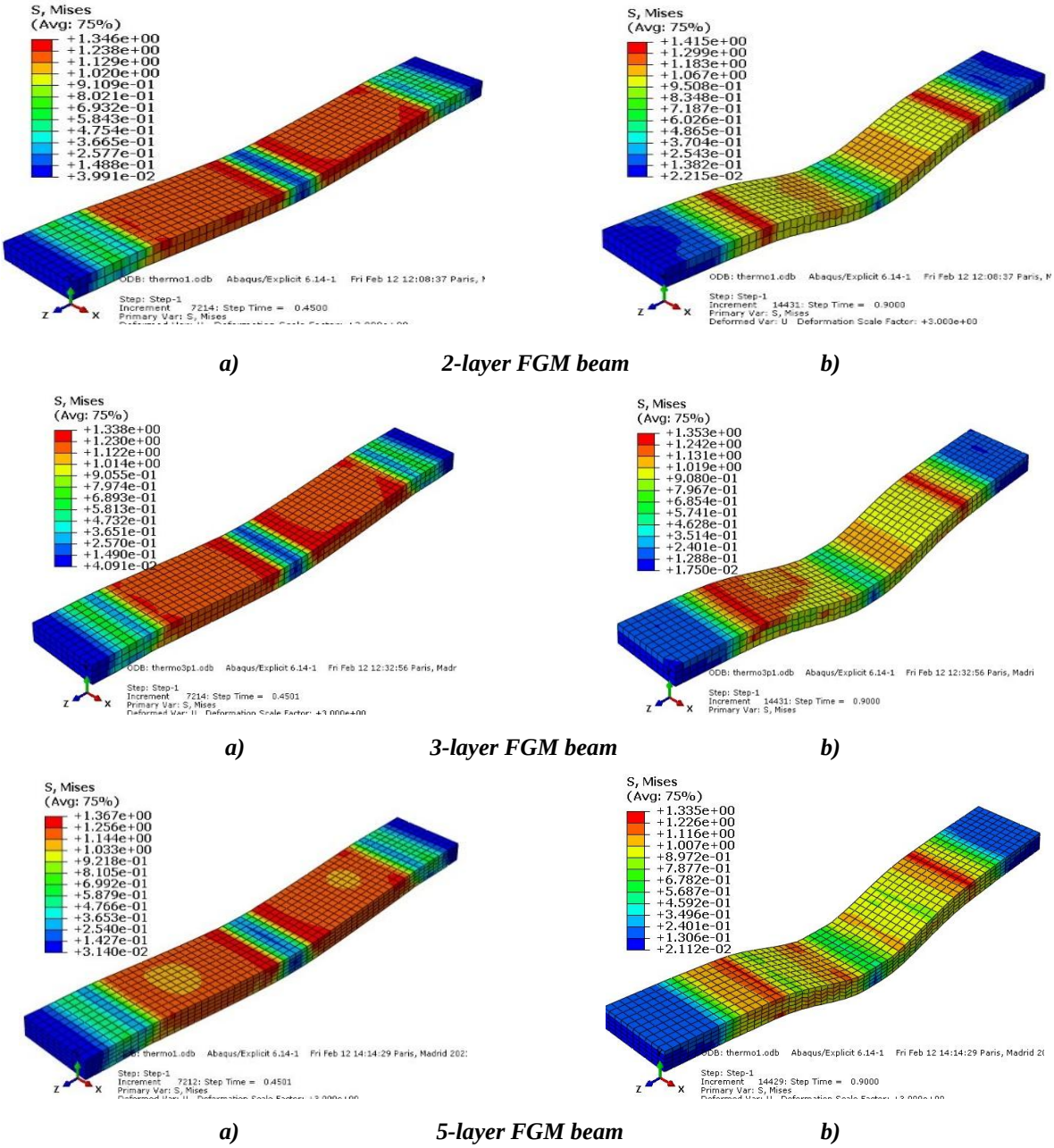


Fig.7 - Stress contours in the unit gradient parameter FGM beams under thermomechanical loading: a) Onset of plastic deformation; b) Fully developed plastic state.

The comparison between mechanical and thermo-mechanical loading shows that temperature significantly amplifies the influence of both the power-law index *p* and the number of discretization layers. Under purely mechanical bending, a low *p* concentrates the stiffer constituent near the faces, leading to higher stresses at the outer fibers and localized plasticity at mid-span, while higher *p* values promote smoother stress diffusion through the thickness. Under thermo-mechanical loading, this contrast becomes more pronounced: thermal expansion inconsistency and stiffness degradation intensify stress concentrations for low *p*, causing earlier yielding and a wider plastic zone. Conversely, higher *p* provides a more gradual redistribution of combined thermal and bending stresses, resulting in a more stable stress pattern. Similarly, increasing the number of layers has a moderate effect in the purely mechanical case, but under thermo-mechanical conditions it becomes critical: finer discretization reduces interlayer stress jumps, limits thermal stress divergence, thereby improving global stability and delaying damage initiation in flexion.

5 Conclusion

In this work, a full three-dimensional nonlinear finite element model was established to explore the flexural behavior of FGM sandwich beams under mechanical and thermo-mechanical loading. The numerical model was first validated against test data for a non-FGM configuration, ensuring the reliability of the adopted material laws, contact conditions, and boundary assumptions. The validated framework was then extended to functionally graded cores using a power-law distribution and different numbers of discretization layers. The gradient index is the key governing parameter controlling stiffness, plastic evolution, and ductility. By modifying the through-thickness material distribution, the power-law index regulates stress localization and the onset of yielding: low *p* increases rigidity but promotes earlier plastic concentration at the outer fibers, while higher *p*leads to smooth stress redistribution and improved ductile response.

The number of discretization layers underlined negligible influence on ultimate load and stresses, while, affects the quality of stress redistribution. Finer discretization reduces stress barriers, leading to more realistic plastic zone development and slightly improved numerical stability. Furthermore, under purely mechanical loading, the behavior is bending-dominated, with plasticity initiating at the tensile/compressive faces and progressively propagating toward the core, depending on the gradation profile. However, under thermo-mechanical loading, thermal softening and differential expansion accelerate yielding, enlarge the plastic zone, and increase stiffness degradation, making the structural response more sensitive to the gradation profile.

Functional gradation enhances ductility and stress regularization under combined loading, contributing to a more stable post-yield behavior, while a limited number of layers remain sufficient to provide accurate predictions with reduced computational cost. Accordingly, future works may extend the present model toward progressive damage and failure prediction, including debonding at skin–core interfaces and fracture initiation within the graded core. Incorporating temperature-dependent material laws and creep effects would allow a more realistic assessment under severe thermo-mechanical environments.

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