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Creep Buckling of Al–SiC Beam

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Abstract

This study presents a finite element model for the analysis of creep buckling of a functionally graded Al–SiC composite beam with continuously varying material properties. The creep behaviour is described using the Norton–Bailey creep law, with parameters obtained from experimental data and interpolated to represent material gradation. A one-dimensional spatial finite element formulation is employed to simulate nonlinear buckling behaviour and predict critical creep buckling times.

The developed model is validated through comparison with a FEMAP shell model, showing good agreement in the obtained results. The influence of material gradation and loading conditions on creep response is also investigated. The results demonstrate that the proposed approach provides an efficient and reliable tool for analysing creep buckling in functionally graded composite structures.

Keywords: creep buckling, functionally graded materials, Al–SiC composite, finite element method, beam modelling, numerical analysis

1 Introduction

The analysis of time-dependent instability phenomena such as creep buckling is of considerable importance in the design of engineering structures operating under high temperatures and sustained loading conditions. Functionally graded materials (FGMs) are particularly attractive in such applications due to their continuously varying material properties, which improve structural performance and reduce stress concentrations. Among these, Al–SiC composites have gained significant attention owing to their favourable mechanical and thermal characteristics.

The accurate prediction of creep buckling behaviour in FGM structures remains a challenging problem. The time-dependent nature of creep deformation, combined with spatial variation of material properties, requires reliable numerical models capable of capturing both effects. While analytical solutions are available for relatively simple cases, practical engineering applications typically rely on numerical approaches, most commonly based on the finite element method.

In this study, the creep behaviour of the material is described using the Norton–Bailey creep law. The creep parameters are obtained by interpolation of available experimental data reported in [1], enabling the representation of continuous distribution of material properties along the beam.

At first, critical buckling loads are determined in eigenvalue manner for several cases of axially loaded cantilever beams made of functionally graded Al–SiC composite material using the developed mathematical model. The obtained results are validated through comparison with numerical simulations performed in FEMAP.

Subsequently, a nonlinear analysis is carried out to determine the load vs displacement curves.

The time-dependent response of the structure is then evaluated, allowing the prediction of creep buckling behaviour under sustained loading conditions.

Based on the computed critical loads, creep analyses are performed at load levels lower than critical ones so buckling behaviour occur due to the creep at some finite time so called critical buckling time.

The study aims to provide a numerical framework for analysing creep buckling in functionally graded composite beams. In addition, the influence of parameters such as material gradation and load level on the structural response is examined.

The results also give a clearer picture of how the material radation affects the stability of the beam over time. This can be useful in the early stages of design, where quick and reliable estimates of creep behaviour are needed.

2 Creep behaviour of FG material

The creep behaviour is described using the Norton–Bailey law,

$$\dot{\varepsilon} = B(y)\,\dot{\sigma}^{\,n(y)} \tag{1}$$

with material parameters obtained through a rigorous interpolation of the diagram presented by Pandey et al. [9], as originally studied by Singh and Ray [6].

Based on this methodology, explicit relationships were derived to express the dependence of creep parameters on temperature (T), applied stress (σ), particle size (d), and reinforcement content (C), tailored to the specific Al–SiC system considered:

$$\log B = -29 + 1729.38 \log \sigma - 274.71 \log T - 1.98 \log d - 15.88 \log C \tag{2}$$

$$\log n = -21.54 \log \sigma + 3.80 \log T + 0.07 \log d + 0.07 \log C \tag{3}$$

These expressions were subsequently employed to determine the Norton–Bailey parameters for each discretized layer of the composite, enabling an accurate representation of the time-dependent creep response under the imposed loading and environmental conditions. The adopted approach ensures consistency with experimentally observed trends and provides a reliable basis for numerical simulation of long-term material behaviour.

For the numerical implementation, the cross-section is discretized into several layers, with each layer assigned material properties based on the local volume fraction. Such a discretization strategy allows for a refined and continuous approximation of material gradation, capturing the influence of reinforcement distribution on both elastic and creep responses with high fidelity.

The material gradation in the Al–SiC composite is defined by the volume fraction function:

$$V_c = \left(\frac{y}{h} + \frac{1}{2}\right)^p \tag{4}$$

where h is the cross-section height and p is the gradation exponent governing the distribution profile of the reinforcement phase. This formulation enables a smooth and continuous transition of material composition through the thickness, avoiding abrupt changes in mechanical properties and ensuring improved structural performance under loading conditions.

The selected Al–SiC composite considered in this study is characterized by a continuous variation of the ceramic volume fraction, ranging from $V_c = 0.1$ at one surface to $V_c = 0.3$ at the opposite surface. This gradual variation defines a functionally graded material (FGM), in which the mechanical properties evolve smoothly across the thickness, thereby reducing stress concentrations and enhancing structural efficiency.

3 Results

In this section, the numerical results obtained using the developed finite element model are presented and discussed. The analysis includes the determination of the critical buckling time applying the beam model originally developed by authors and detailly explained in ref. [2].

For validation purposes the FEMAP comercial code simulations were run.

The cantilever beam of length $L = 160$ cm with a rectangular cross-section of 5×2 cm, as shown in Figure 1 is considered.

The beam is subjected to an axial compressive force applied at the free end. The material is a functionally graded Al–SiC composite, with properties varying continuously along the thickness direction.

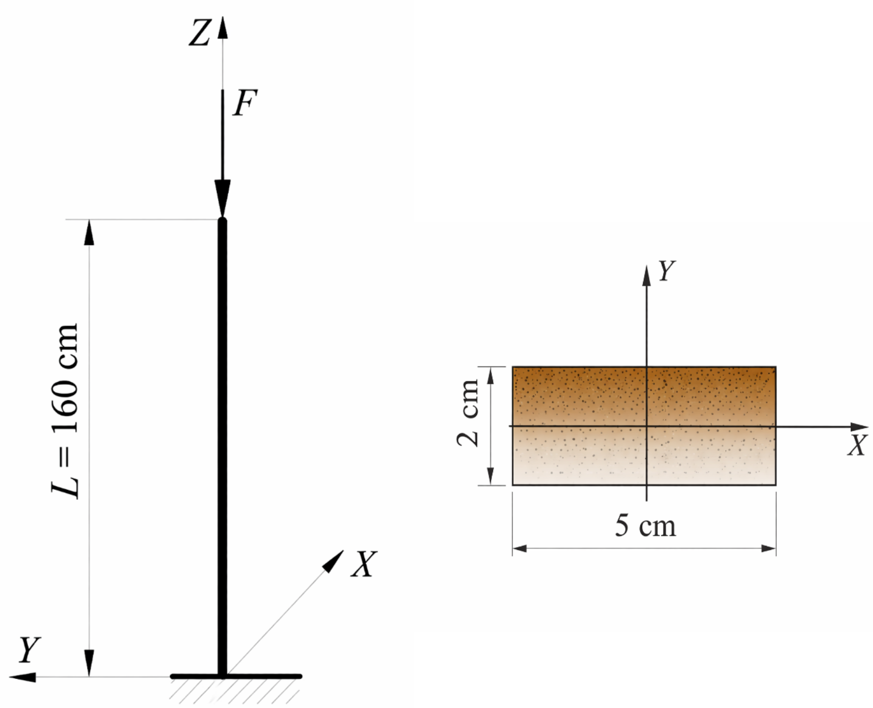

Figure 1: Geometry of the functionally graded cantilever beam and its cross-section.

The material properties of the constituent phases are taken as $E_{Al} = 70$ GPa for aluminum and $E_{SiC} = 410$ GPa for silicon carbide. The effective modulus in each layer is evaluated according to the local volume fraction, ensuring consistency with the graded material model. A constant Poisson's ratio $\nu = 0.3$ is assumed for all layers, which represents a common and sufficiently accurate approximation for the present analysis.

The time-dependent deformation was evaluated using the Norton–Bailey creep law, with material parameters adopted from the reference study.

The corresponding creep parameters across the cross-section are summarized in Table 1, assuming the discretization into a 20 layers providing a detailed overview of the variation in stiffness and time-dependent behaviour throughout the thickness of the beam.

The critical buckling load was first determined using the developed numerical model and independently verified using FEMAP simulations. Both approaches yielded

Table 1: Variation of material and creep parameters through the cross-section

$E(y)$ [GPa]	$B(y)$ [MPa^{-n} s^{-1}]	$n(y)$
170.3	2.2352×10^{-38}	17.513
166.9	3.86505×10^{-38}	17.471
163.5	6.81534×10^{-38}	17.428
160.1	1.22729×10^{-37}	17.382
156.7	2.26065×10^{-37}	17.336
153.3	4.26711×10^{-37}	17.287
149.9	8.27053×10^{-37}	17.237
146.5	1.6498×10^{-36}	17.184
143.1	3.396×10^{-36}	17.130
139.7	7.23502×10^{-36}	17.073
136.3	1.60082×10^{-35}	17.013
132.9	3.69321×10^{-35}	16.951
129.5	8.92579×10^{-35}	16.885
126.1	2.2722×10^{-34}	16.815
122.7	6.1323×10^{-34}	16.742
119.3	1.76835×10^{-33}	16.664
115.9	5.50035×10^{-33}	16.581
112.5	1.86707×10^{-32}	16.492
109.1	7.01793×10^{-32}	16.396
105.7	2.97581×10^{-31}	16.292

a critical load of $F_{cr} = 4430$ N, indicating excellent agreement between the two models.

To further validate the obtained value, a nonlinear static analysis was performed. The relationship between the applied load and the resulting displacement at the free end is shown in Figure 2.

As the displacement increases, the load asymptotically approaches 4430 N, which corresponds to the critical buckling load. This behaviour is characteristic of instability problems, where the structure loses stiffness as it approaches the critical state. The convergence of the nonlinear solution towards the same value obtained from eigenvalue analysis confirms the consistency and correctness of the model. Furthermore,this agreement indicates that the numerical formulation is capable of reliably capturing both the pre-buckling response and the onset of instability.

Following the determination of the critical load, a creep analysis was conducted under a constant compressive force equal to $0.85F_{cr}$, corresponding to 3800 N. This load level was selected to ensure significant creep effects while maintaining a finite time to instability, allowing for a clear observation of all stages of the creep process.

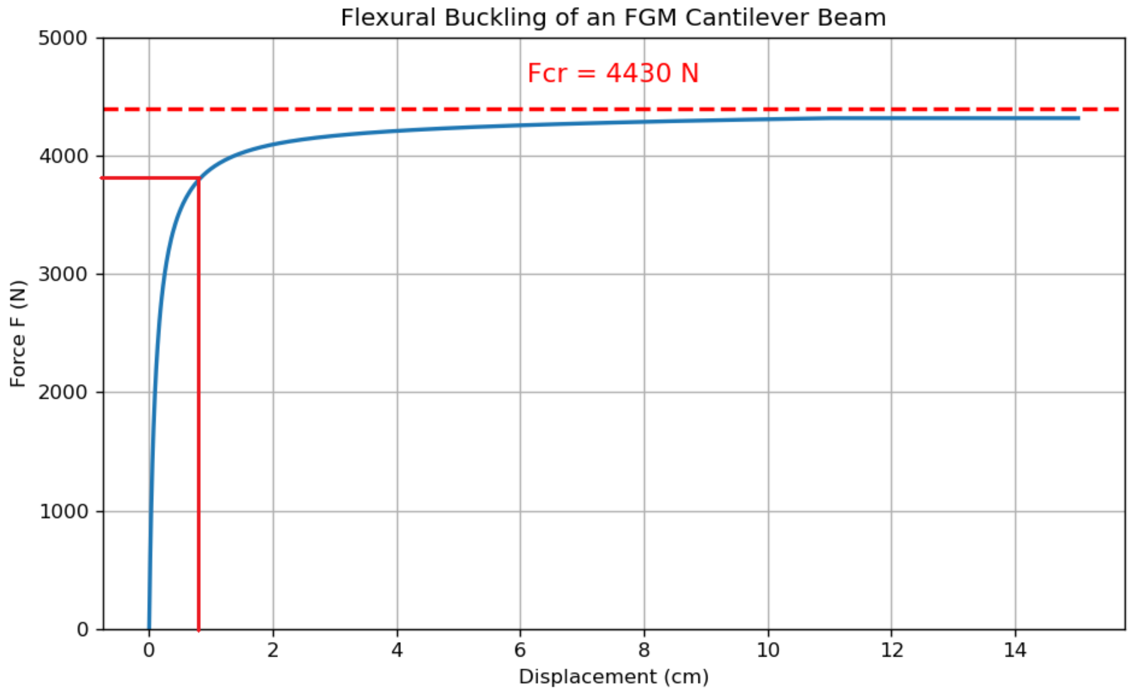

Figure 2: Load–displacement curve obtained from nonlinear static analysis.

The evolution of displacement at the free end as a function of time is shown in Figure 3 for three different models: the FEMAP shell and solid as well as beam own ones.

The comparison enables an assessment of the accuracy and reliability of the proposed formulation.Obtained critical buckling time $t_{cr} = 900 \cdot 10^3$ h of defines the service life of the structure under sustained loading conditions.

The results show good agreement between the different approaches, with only minor deviations observed. The developed model predicts a critical time that lies between the shell ($860 \cdot 10^3$ h) and solid ($920 \cdot 10^3$ h) solutions, indicating a consistent and balanced representation of the structural behaviour. Furthermore, the close agreement between the resultsconfirms that the beam formulation capable of capturing the essential features of creep-induced instability with satisfactory accuracy.

4 Concluding remarks

In this paper, a numerical approach for the analysis of creep buckling in functionally graded Al–SiC composite beams has been presented. The developed one-dimensional finite element model incorporates spatial variation of material properties and time-dependent behaviour described by the Norton–Bailey creep law.

The obtained results demonstrate that the proposed modelling approach is capable

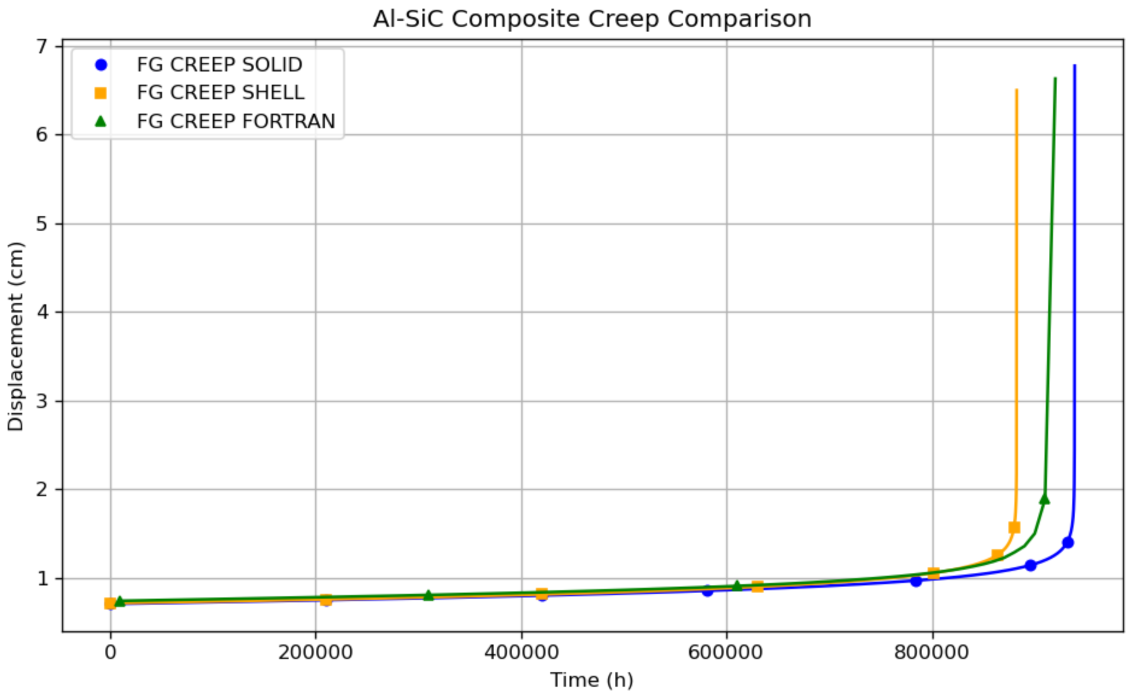

Figure 3: Comparison of creep displacement evolution for different numerical models.

of accurately capturing both the instantaneous and time-dependent behaviour of functionally graded beams. The agreement with FEMAP results confirms the validity of the formulation.

The slight differences in predicted creep times can be attributed to differences in modelling assumptions between beam, shell, and solid formulations.

The developed one-dimensional model, despite its simplicity, provides results that are in close agreement with both approaches.

Furthermore, the results highlight the significant influence of creep on structural stability. Even at a load level below the critical buckling load, the structure eventually loses stability due to time-dependent effects. This emphasises the importance of considering creep effects in the design of functionally graded composite structures subjected to sustained loading lower than the critical ones.

Overall, the proposed numerical model offers an efficient and reliable tool for predicting creep buckling behaviour, with significantly lower computational cost compared to full three-dimensional analyses.

Future work may include the extension of the model to more complex geometries and various boundary conditions.

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