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Buckling of non-uniformly heated isotropic beam: Experimental and theoretical investigations

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ABSTRACT

Influence of non-uniform heating on critical buckling temperature of an aluminium beam has been investigated experimentally with the help of a novel experimental set-up developed in-house. Non-linear finite element analysis, considering the initial geometric imperfection, has been carried out to compare the experimentally obtained typical load-deflection curve. The linear critical buckling temperature predicted numerically are validated with analytical solutions. Experimental results revealed that critical buckling temperature of the non-uniformly heated beam greatly differs from the uniformly heated beam. It is also observed that the location of heat source and resulting non-uniform temperature variation influences the critical buckling temperature significantly.

1. Introduction

Most of the engineering structures in automotive, military and aerospace industries are nowadays slender in nature to minimise the gross weight. Aluminium which is light in weight and corrosion resistant stands out to be a competent material in these industries. Beams are one kind of structure that are used in automobile, machinery and other kind of structural frames which can be subjected to adverse conditions like thermal load and moisture during their operation. The investigation of thermal buckling has various issues and summary of the recent literatures are presented by Tauchert [1] and Thornton [2].

Numerous research was carried out several decades before on structures that are subjected to thermal load which are mostly uniform and are solved analytically. Cotterell and Parkes [3] analysed the buckling mode shapes of circular plates that are subjected to centre heating and edge heating. Biswas [4] analysed the thermal buckling behavior of orthotropic plates having different geometry and edge constraints using Galerkin's approach. Bargmann [5] investigated analytically, an isotropic initially stress free and initially stressed [6] elastic plate that are subjected to temperature field for simply supported edge constraints. Sharifian [7] computed the critical buckling loads of isotropic rectangular plates having two simply supported opposite edges and the other two supported against rotation. Datta [8] obtained the critical buckling temperature of heated equilateral triangular and elliptical plate resting on elastic foundation. Fu et al. [9] obtained the analytical solutions for the thermal buckling of symmetric laminated composites having different boundary conditions. Several researchers employed approximate methods to solve buckling of structures subjected to different type of loads. Matsunaga [10] obtained the buckling stresses on multilayered composite beams using approximate theories. Jones [11] obtained the critical buckling temperature of bars that are restrained from expanding under thermal load assuming temperature dependent properties. Aydogdu [12] obtained the critical buckling temperature for cross-ply laminated composite beams with different combinations of hinged and clamped edge constraints using the Ritz method. Gupta et al. [13] using finite element and intuitive formulations investigated the thermal post buckling behavior of slender and shear flexible columns under different boundary conditions. Theses studies revealed that the thermal buckling behavior and the critical buckling strength are significantly influenced by the nature of the boundary conditions. Gunda [14] has carried out the thermal post buckling behavior of Timoshenko beams with different boundary conditions using Rayleigh Ritz method and has drawn a similar conclusion. The simply supported ends had the maximum thermal post buckling deflection for the same external thermal load. These studies bring-forth the influence of boundary constraints on the buckling strength of structures.

With the advancement of technology, numerous studies were carried out on the buckling behavior of structures composed of different material properties having different edge constraints subjected to distinct non-uniform temperature fields using the Finite Element Method (FEM). Critical buckling temperature of

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rectangular panels when they are subjected to camel humped temperature profile heating is analysed for different boundary conditions by Ko [15]. Jeyaraj [16] investigated the buckling and the free vibration behavior of isotropic plates subjected to arbitrarily varying temperature fields. The influence of free edge on the critical buckling temperature and the corresponding mode shapes are detailed in the study. The impact of non-uniform temperature profiles on the thermal buckling behavior of anisotropic panels are investigated by Li et al. [17]. These studies bring-forth the role of non-uniform temperature profile on the thermal buckling behavior of structures. It was observed a structure subjected to centre heating in comparison edge heating had significant influence on the thermal buckling behavior. The thermal loading significantly influences other characteristics such as vibration and acoustics [18] of structures and varies significantly with the nature of thermal loading. A detailed study on non-linear buckling behavior of cylindrical shells composed of different material composition was carried out by Alijani et al. [19] to investigate the influence of different factors such as geometric and imperfection parameters on pre and post-buckling paths.

However, less investigations were carried out experimentally for their behavior when subjected to non-uniform temperature field. Murphy and Ferriera [20] obtained the critical buckling temperature of plates subjected to uniform temperature rise and compared the experimental results with an analytical approach based on the von-karman plate theory which showed good agreement. Numerical and experimental investigations were carried out to investigate the buckling and post-buckling behavior of composite tubes with square cross-section by Czapski and Kubaik [21] and the models were validated with FEM. For a uniform distribution of thermal load, the thermal buckling of a circular isotropic plate and laminated composite plate is investigated by Jin et al. [22,23] using digital image correlation. They obtained the critical buckling temperature and the corresponding mode shapes. Dynamic and acoustic behavior on thermal pre-buckled and post-buckled plates which are uniformly heated were analysed experimentally by Geng et al. [24]. It was observed that stresses are getting generated due to the applied load which causes buckling of the structure.

It was observed that, the non-uniform thermal load has significant impact on the buckling strength of structures such as plates and beams. A structure that is exposed to edge heating has higher buckling strength than a structure exposed to centre heating and also whenever the area of the structure exposed to the highest temperature of a temperature profile increases the buckling strength correspondingly decreases. The loose constraints at the edges gave lower buckling strength compared to the tight constraints. The non-uniform thermal loads were found to significantly influence the buckling strength of any structure that has different edge constraints.

Most of the investigations were carried out on beams or plates that are subjected to uniform heating above ambient or through the thickness temperature variation [25]. However, non-uniform longitudinal thermal distribution was analysed with the help of finite element method in detail. In literatures, it was reported that the critical buckling temperature is significantly influenced by the nature of temperature profile, aspect ratio, thickness ratio and structural boundary conditions. Limited experimental studies were performed to analyse the thermal buckling behavior of the structure that were subjected to uniform temperature distribution and it is important to analyse critical buckling temperature of non-uniformly heated structures also experimentally. Therefore, the present paper emphasizes on the influence of nature of temperature profile and beam aspect ratio on the thermal buckling behavior of an isotropic beam.

2. Research subject and scope

The literature survey reveals that the nature of temperature variation influences critical buckling temperature of structures exposed to elevated temperature. It was also found that only limited experimental studies were carried out on the thermal buckling behavior of structures. An experimental technique, developed in-house, was employed to investigate critical buckling temperature of non-uniformly heated beams made of aluminium. Beams with different length/height and length/thickness ratio were investigated for thermal buckling under four different temperature variations, across the length of the beam as shown in Table 1. Results obtained from the linear buckling analysis is compared with the closed form solutions for the beams with C-C boundary condition. Experimental and numerical investigations were carried out for clamped-clamped (C-C) boundary condition.

3. Methodology

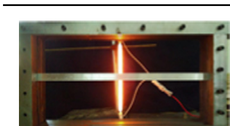
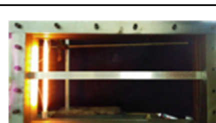
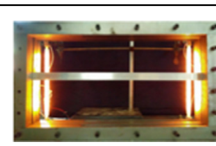
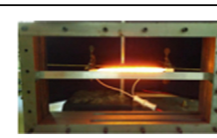
3.1. Experimental investigation

The critical buckling temperature of an isotropic beam rectangular cross-section as shown in Fig. 2, exposed to different types of non-uniform temperature variations across the length (L) of the beam were investigated experimentally with the help of an in-house developed experimental set-up as shown in Fig. 1. The numerical results were compared with experimental results for validation. Finite element method was used to perform the numerical investigations..

The various components used in the experimental test rig and their specifications are listed as follows.

- **Fixture**: A mild steel rectangular fixture as shown in Fig. 3 was used to mount the beam firmly along the two opposite short edges to simulate the clamped-clamped (C-C) boundary condition. The fixture consists of four different rigid frames as shown in Fig. 3. A provision has been made on the fixture to move one of the two shortest end of the fixture in order to accommodate

Table 1
IR Heater position for different temperature profiles.

Case (a)	Case (b)	Case (c)	Case (*d*-i)
 Heater at the centre $\left(x = \frac{L}{2}\right)$	 Heater at left fixed end (x=0)	 Heater at fixed ends ($x = 0$; $x = L$)	 Heater along the longitudinal direction