BUCKLING AND NONLINEAR RESPONSE OF SANDWICH PANELS WITH TEMPERATURE DEPENDENT CORE PROPERTIES

Ole T. Thomsen*, Yeoshua Frostig**
***Department of Mechanical Engineering, Aalborg University, Denmark**
****Faculty of Civil Engineering, Technion - Israel Institute of Technology, Israel**

Keywords: *sandwich structures, thermal buckling & post-buckling, non-linear response, geometric non-linearity, "soft" core, temperature-dependent properties*

Abstract

The paper deals with the buckling response and non-linear behaviour of sandwich panels with "soft" cores with temperature-dependent mechanical properties subjected to thermally induced deformations and mechanical loads.

The study investigates the effects of the degradation of mechanical properties as a result of rising temperature. The formulation is based on the high-order sandwich panel (HSAPT) approach, which takes into account the flexibility of the core in the vertical direction, as well as the dependency of the mechanical core properties of the temperature distribution through the core depth. The stress and deformation fields of the core have been derived analytically.

The buckling equations are derived using the perturbation technique, and the critical temperatures and modes of local and global buckling are determined through the solution of non-linear algebraic equations.

Numerical results obtained for different temperature distributions, different boundary conditions and the simultaneous action of thermal and mechanical loads are presented. It is shown that an unstable non-linear response occurs when external mechanical and thermal loads act simultaneously on an unrestrained sandwich panel.

1 Introduction

Structural sandwich panels are used for a variety of applications in just about all major industries. They are usually made of two face sheets made of either metal or composite laminated materials that are separated and bonded to a low-strength compliant core material. The use of sandwich structures is on the increase, as primary and secondary structural components, due to their superior qualities in terms of high strength to weight and stiffness to weight ratios, ease of manufacturing, acoustic and thermal insulation, and flexibility in design. Sandwich structures are often subjected to aggressive service conditions including elevated temperatures, which lead to thermally induced deformation loads and degradation of the material properties, in addition to external mechanical loads.

In general, the material properties of the constituents of a sandwich panel depend on the temperature field imposed on the structure. However, this dependency is usually ignored in engineering analysis and design, even for applications/cases where temperature fields are induced and the material properties degrade significantly with increasing temperatures. In many sandwich panel applications, the core material is made from polymer foam where significant changes in the properties may occur in the operating range of temperatures of the structure. For example, a Rohacell type of foam looses its heat distortion resistance at about 200^{o}C, [1], while Divinycell foam looses its strength at about 80-100^{o}C [2-3]. Hence, it becomes extremely important to understand how the degradation of the core properties, thermally induced deformation loads and large deformations affects the buckling and the non-linear response of sandwich panel with "soft" cores made of polymer foam.

The response of a sandwich panel when subjected to an external mechanical load may involve a stable type of non-linear response (such as a plate type of buckling response), or an unstable response (like the buckling response of a beam or a shell) depending on the geometrical and mechanical properties of the sandwich constituents as well as the boundary conditions. Moreover, when external mechanical loads act simultaneously with thermal loads (rising temperatures), the degradation of the material properties with rising temperature may shift the response from being linear and stable into being unstable. Little is known about the occurrence and severity of such effects, which are therefore studied in this investigation.

Sandwich panels with vertically rigid cores made of metallic or polymer honeycombs have been considered by many researchers. It is usually assumed that the core is “anti-plane” and incompressible, see the textbooks by Allen [4] and Zenkert [5]. Usually, the models adopted for predicting the linear and non-linear load-response of sandwich panels are based on the “equivalent single layer” approach (ESL), where the layered panel is replaced by an equivalent single layer with homogenized (equivalent) mechanical properties, see Mindlin first-order theory [6], and Reddy's high-order theories [7]. The classical sandwich, ESL and high-order models usually disregard the changes in the height of the core (i.e. the compressibility) when the panel is deformed.

Thermal buckling and non-linear analyses using the ESL approach and assuming mechanical properties that are *independent* of temperature have been considered by a few authors, e.g. Tessler *et al.* [8] and Liew *et al.* [9] who based their works on a First Order Shear Deformation (FOSD) models.

Only a few research works have addressed the response of sandwich panels with *temperature-dependent* mechanical properties, including Chen and Chen [10] and [11], Gu and Asaro [12], Birman, [13], Birman *et al.* [14] and Lie *et al.* [15]. These works are based either on classical sandwich, ESL/FOSD or high-order models, and they all disregard the changes in the height of the core (compressibility) during the deformation of the sandwich panel. Accordingly, they yield inaccurate results when used for sandwich panels with a “soft/compliant” core, e.g. like a polymer foam

An approach that models the layered sandwich panel as made of two face sheets and a core layer that are interconnected through fulfilment of equilibrium and compatibility conditions, and thus is able to incorporate the vertical flexibility of the core, offers significant advantages when considering sandwich structures with compliant/”soft” cores. This approach has been implemented through a variational principle into the High-Order Sandwich Panel Theory (HSAPT), and has been successfully used for the analysis of various linear and non-linear sandwich panel problems. A brief list of references include: Frostig [16], Frostig and Baruch [17], Frostig [18], Sokolinsky and Frostig [19], Frostig *et al*. [20]. Recently, Frostig and Thomsen [21] and [22] used the HSAPT approach to investigate the thermal buckling and non-linear response along with localized effects of sandwich panel with a compliant/“soft” core assuming temperature independent or averaged mechanical properties.

The literature survey reveals that most studies have ignored the effects associated with the vertical flexibility of the core. Moreover, they have not addressed the non-linear interaction response when the mechanical and the thermal loads are applied simultaneously.

The present analysis incorporates the flexibility of the core in the vertical direction, the thermally induced deformations and mechanical loads along with non-uniform core properties resulting from temperature dependency, into the mathematical modelling according to the High-Order Sandwich Panel Theory (HSAPT) approach.

2 Modelling

2.1 Restrictive Assumptions

The formulation presented herein is based on the following ”classical” assumptions for sandwich structures with compliant cores: The face sheets possess in-plane and bending rigidities; the face sheets and the core material are assumed to be linear elastic; the face sheets undergo large displacements and moderate rotations (geometrical non-linearity); the core is considered as a 2D linear elastic continuum with kinematic relations that correspond to small deformations (geometrically linear), where the core height may change during deformation, and section planes do not remain plane after deformation; the core possesses only shear and transverse normal stiffness, whereas the in-plane (longitudinal) normal stiffness is assumed to be nil; thermal fields are applied to the face sheets and the core with temperature dependent mechanical properties; full bonding is assumed between the face sheets and the core; and the mechanical loads are applied to the face sheets only.

Temperature dependent material properties of the core are implemented into the governing equations through closed-form solutions of the governing core equations. For simplicity, the face sheets are assumed to be isotropic and to have temperature independent mechanical properties. The buckling equations are derived following the perturbation approach. Results of a numerical study investigating the effects of the temperature-dependent mechanical properties on the buckling and interaction response of thermal and mechanical loads is presented.

2.2 Nonlinear Governing Equations

The set of non-linear governing equations used for the analysis herein have been derived through the minimization of the total potential energy following the procedure presented in Frostig and Thomsen [21] and [22]. Due to the limited number of pages available, only a brief selection of the governing equations are given herein. Instead the reader is referred to Frostig and Thomsen [23].

The non-linear thermal field equations for the sandwich panel read:

$$-\left(\frac{d}{dx}N_{xxt}(x)\right)-\tau_{ct}(x)\,b_w-n_t=0 \tag{1}$$

$$-N_{xxt}(x)\left(\frac{d^2}{dx^2}w_t(x)\right)-\left(\frac{d}{dx}N_{xxt}(x)\right)\left(\frac{d}{dx}w_t(x)\right)-\frac{1}{2}b_w\,d_t\left(\frac{d}{dx}\tau_{ct}(x)\right)-\left(\frac{d^2}{dx^2}M_{xxt}(x)\right)$$
$$-\sigma_{zzt}(x)\,b_w+\left(\frac{d}{dx}m_t(x)\right)-q_t=0 \tag{2}$$

$$-\left(\frac{d}{dx}N_{xxb}(x)\right)+\tau_{cb}(x)\,b_w-n_b=0 \tag{3}$$

$$-N_{xxb}(x)\left(\frac{d^2}{dx^2}w_b(x)\right)-\left(\frac{d}{dx}N_{xxb}(x)\right)\left(\frac{d}{dx}w_b(x)\right)-\frac{1}{2}b_w\,d_b\left(\frac{d}{dx}\tau_{cb}(x)\right)-\left(\frac{d^2}{dx^2}M_{xxb}(x)\right)$$
$$+\sigma_{zzb}(x)\,b_w+\left(\frac{d}{dx}m_b(x)\right)-q_b=0 \tag{4}$$

$$-\left(\frac{\partial}{\partial z_c}\tau(x,z_c)\right)b_w=0 \tag{5}$$

$$-\left(\frac{\partial}{\partial x}\tau(x,z_c)\right)b_w-\left(\frac{\partial}{\partial z_c}\sigma_{zz}(x,z_c)\right)b_w=0 \tag{6}$$

The isotropic constitutive relations of the face sheets and the core yield the following additional load-displacement equations:

For the face sheets (j=t,b):

$$N_{xxt}(x)-EA_j(x)\left(\left(\frac{d}{dx}u_{oj}(x)\right)+\frac{1}{2}\left(\frac{d}{dx}w_j(x)\right)^2\right)+EA_j(x)\,\alpha_j\left(\frac{1}{2}T_{j_t}(x)+\frac{1}{2}T_{j_b}(x)\right)=0 \tag{7}$$

$$M_{xxj}(x)=EI_j\left(-\left(\frac{d^2}{dx^2}w_j(x)\right)-\frac{\alpha_j\,(T_{j_b}(x)-T_{j_j}(x))}{d_j}\right) \tag{8}$$

For the core:

$$\frac{\sigma_{zz}(x,z_c)}{E_c(T_c(x,z_c))}=\left(\frac{\partial}{\partial z_c}w_c(x,z_c)\right)-\alpha_c\,T_c(x,z_c) \tag{9}$$

$$\frac{\tau_c(x,z_c)}{G_c(T_c(x,z_c))}=\left(\frac{\partial}{\partial z_c}u_c(x,z_c)\right)+\left(\frac{\partial}{\partial x}w_c(x,z_c)\right) \tag{10}$$

where $T_c(x, z_c)$ is the temperature distribution within the core that equals:

$$T_c(x, z_c) = T_{c_t}(x)\left(1 - \frac{z_c}{c}\right) + \frac{T_{c_b}(x)\, z_c}{c} \qquad (11)$$

and where the following refers to terms/quantities of the two face sheets: N_{xxj} and M_{xxj} are the in-plane and bending moment stress resultants of each face sheet; w_j and u_{oj} are the vertical and mid-plane in-plane displacements of the face sheets; EA_j and EI_j are the in-plane and flexural rigidities, respectively; d_j is the thickness of the face sheets; α_j is the coefficient of thermal expansion of the face sheets; $T_{j_k}(x)$ *(k=t,b)* are the temperatures at the upper and lower fibres of the faces, respectively; σ_{zzj} and τ_{cj} are the vertical normal and shear stresses at the face-core interfaces, respectively; b_w is the width of the panel, and x is the longitudinal coordinate of the panel. The terms/quantities related to the core include: $\tau_c(x, z_c)$ and $\sigma_{zz}(x, z_c)$ are the shear and the vertical normal stresses; $E_c(T_c x, z_c)$ and $G_c(T_c x, z_c)$ are the vertical modulus of elasticity and the shear modulus, respectively; $w_c(x,z_c)$ and $u_c(x,z_c)$ are the vertical and in-plane displacements, respectively; α_c is the coefficient of thermal expansion, $T_{c_k}(x, z_c)$ *(k=t,b)* are the temperatures at the upper and lower fibres of the core, respectively; c is the core height, and z_c is the vertical coordinate measured from the upper face-core interface. See Fig. 1 for sign conventions and temperature distributions. The set of the field equations, Eqns. (1) to (4) are given in an inexplicit form, since the face-core interfacial stresses are unknown. In addition, this set of equations does not fulfill the compatibility conditions of a full bond at the upper and the lower face face-core interfaces.

The core stress fields, see Eqns. (5)-(6), yield:

$$\tau_c(x, z_c) = \tau_{ct}(x) = \tau_{cb}(x) = \tau(x) \qquad (12)$$

$$\sigma_{zz}(x, z_c) = -\left(\frac{d}{dx}\tau(x)\right) z_c + \sigma_{zzt}(x) \qquad (13)$$

Thus, the shear stresses within the core are predicted to be uniform and the distribution of the vertical normal stresses through the depth of the core is predicted to be linear. The vertical stress distribution and the displacements fields of the core are derived through the closed form solution of Eqns. (9) and (10); the compatibility conditions of the vertical displacement at the upper and the lower core-face interfaces, and the compatibility condition of the longitudinal displacement at the upper interface. These equations are omitted herein due to their length and complexity, and instead the reader is referred to [23] for the details.

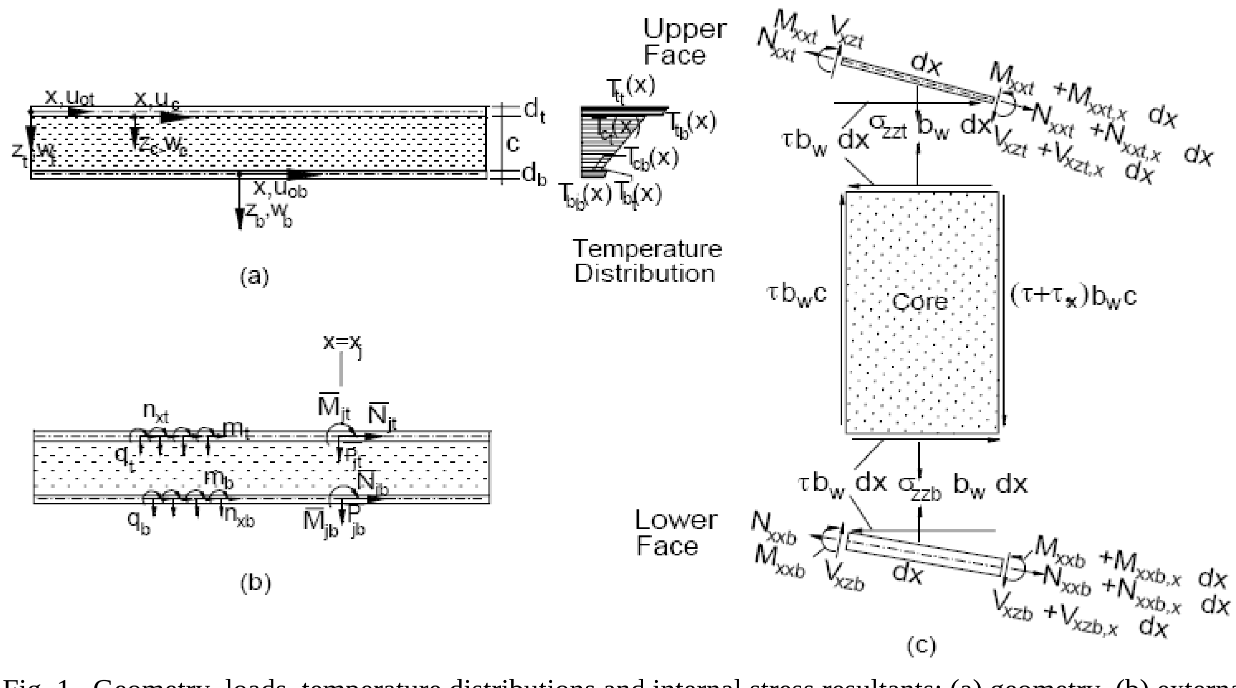

Fig. 1. Geometry, loads, temperature distributions and internal stress resultants: (a) geometry, (b) external loads, (c) internal stress resultants and interfacial normal stresses.

3 Buckling Analysis

The buckling analysis is based on the perturbation approach where the non-linear governing equations are linearised, Simitses [24].

The linearised governing equations for the pre-buckling and buckling stages appear in Frostig and Thomsen [21] for sandwich panels with *temperature–independent* material properties and a uniform temperature field through the length and through the height.

For the case of a sandwich panel with *temperature-dependent* material properties subjected to a longitudinally and vertically uniform temperature field, the critical temperatures, i.e. the wrinkling and global buckling modes, have been derived following the procedure described in Frostig and Thomsen [22]. For this case it is assumed that the two face sheets are of identical geometry and have temperature-independent mechanical properties that are uniform lengthwise, and it is assumed that the core has uniform mechanical properties that depend on the temperature. As a result of the temperature dependency of the core, the critical temperatures can be evaluated only through the solution of a set of non-linear algebraic equations, while for the case where the properties are temperature-independent the critical values can be derived in terms of closed-form expressions, see Frostig and Thomsen. [23].

3.1 Temperature Dependent Core Properties

A numerical study has been conducted to determine the effects of the temperature-dependent properties of the core on the critical temperatures for Rohacell WF and Divinycell P and HP types of foams. Fig. 2 describes the non-dimensional elastic and shear moduli of these materials as functions of temperature. The curve fitted data appearing in Fig. 2 are based on the data in [1] and [3], see [23].

3.2 Critical Temperatures – Divinycell HP and P Grades

The critical temperatures have been determined assuming both temperature independent and temperature dependent core properties for comparison. The results obtained for Divinycell foam cores are given in Table 1. Reference is given to [23] for results obtained for Rohacell foams.

A sandwich beam of length 1000 mm, width 30 mm, two aluminium face sheets of 0.5 mm thickness, CTE of 1e-5, E-modulus of 69.1 GPa and a core of height 25 mm is investigated. Table 1 include the critical temperature for the wrinkling and the global buckling modes, as well as the value of the mechanical properties when the critical values (temperatures) are reached.

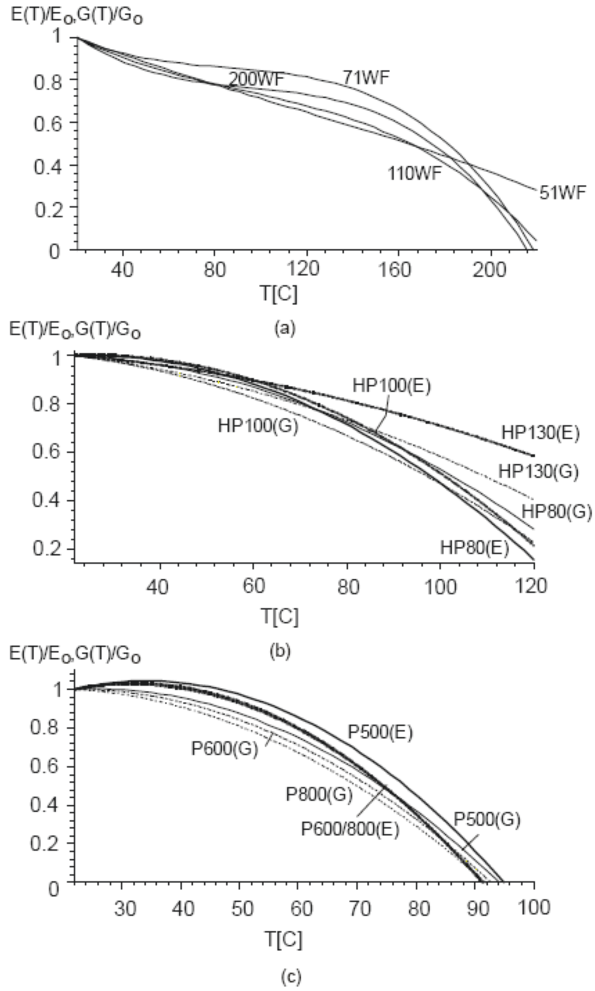

Fig. 2. Normalized temperature-dependent elastic and shear moduli of various polymer foam cores: (a) Rohacell WF foam, (b) Divinycell HP foam, (c) Divinycell P foam. Legends: (E) – modulus of elasticity, (G) – Shear modulus. From [1], [3].

Table 1 (Divinycell HP and P grade cores) reveal that when E and G at room temperature are considered (denoted by TI for “temperature independent” properties), the critical temperatures are much higher than upper range of operating temperatures. However, when the temperature dependency of the core is included in the analyses (denoted by TD for “temperature dependent”), the predicted critical temperatures reach the upper range of the operating temperature of the foam, which is associated with very low E and G values. The differences in the critical temperatures between the TI and TD cases are significant, especially for the wrinkling buckling modes. The differences between the critical values for global buckling are much smaller. For wrinkling buckling mode, the half wave number is significantly reduced compared with the TI case. For most cases the critical buckling mode is associated with global buckling.

The critical values for the HP grade foams are higher then those of the P grade foams. For P grade foams the critical temperatures for wrinkling and global buckling are almost identical, and they are in the upper range of operating temperature for this material.

4 Non-linear Thermo-Mechanical Analysis

4.1 Non-Linear Governing Equations

The non-linear response, for the case of a uniform distribution of the temperature field along the panel length and a linear gradient through its depth, see Fig. 1a, is investigated.

The formulation is based on a set of first-order ordinary differential equations (ODEs), derived from the non-linear equations specified in section 2.2 using well known procedures, Stoer and Bulirsch [25], see [23] for details. The non-linear response was determined numerically using trapezoid or mid-point methods with Richardson extrapolation or deferred corrections, see Ascher and Petzold [26], implemented in the software package Maple.

4.2 Interaction of Mechanical Loads and Thermally Induced Deformations

The non-linear thermo-mechanical response of a restrained and unrestrained sandwich panel loaded by a prescribed mechanical load and a changing thermal gradient is studied.

Notice that a linear response occurs when the loads are applied separately, or when the two loads are applied simultaneously, and the core properties are temperature-independent (TI).

The sandwich panel consists of two face sheets made of Kevlar/epoxy laminates and Divinycell HD-80 core. The layout, dimensions, mechanical properties and loadings appear in Fig. 3a.

Table 1. Critical Temperatures of Divinycell HP and P foams. Legends: Wr- wrinkling mode, Gl – global mode, TI – Temperature –Independent properties, TD – Temperature –Dependent properties. * With respects to room temperature (22°C). ** Modulus of Elasticity and Shear Modulus at room temperature.

Foam	Buckling Types	T_{cr} °[C]*	m	$E_c(T_{cr})$[MPa]	$G_c(T_{cr})$[MPa]
HP80	Wr-TI**	356.4	93	63.6	28.4
	Wr-TD	102.2	50	5.4	2.4
	Gl-TI	140.1	1	63.6	28.4
	Gl-TD	95.0	1	13.8	6.2
HP100	Wr-TI	390.8	97	77.0	36.9
	Wr-TD	106.1	51	5.8	2.8
	Gl-TI	144.2	1	77.0	36.9
	Gl-TD	99.8	1	14.6	7.0
HP130	Wr-TI	462.9	106	105.6	44.9
	Wr-TD	155.2	61	12.5	5.3
	Gl-TI	147.1	1	105.6	44.9
	Gl-TD	128.1	1	39.7	16.9
P500	Wr-TI	371.8	95	72.8	38.9
	Wr-TD	71.9	42	2.7	1.4
	Gl-TI	144.4	1	72.8	38.9
	Gl-TD	70.4	1	6.2	3.3
P600	Wr-TI	455.6	105	106.4	49.7
	Wr-TD	68.5	41	2.4	1.1
	Gl-TI	147.9	1	106.4	49.7
	Gl-TD	67.4	1	6.6	3.1
P800	Wr-TI	550.2	116	153.8	68.6
	Wr-TD	69.0	41	2.5	1.1
	Gl-TI	151.2	1	153.8	68.6
	Gl-TD	68.1	1	7.1	3.1

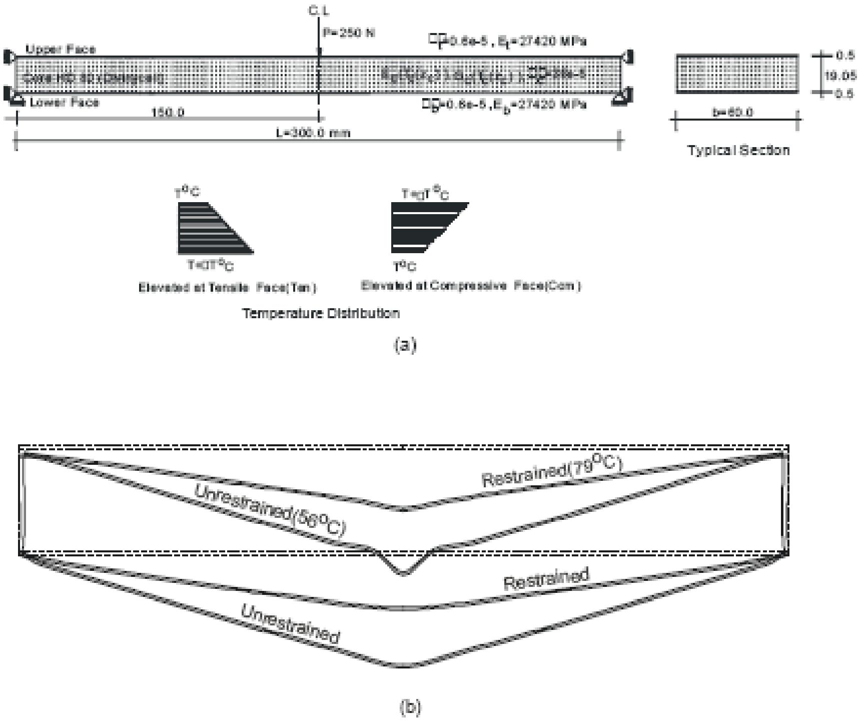

Fig. 3. Geometry and deformed shapes of sandwich panel loaded by a mechanical load and thermally induced deformations with a “zero” thermal gradient: (a) geometry of unrestrained and restrained panels; (b) deformed shape of an unrestrained at T=56°C and a restrained panel at T=79°C.

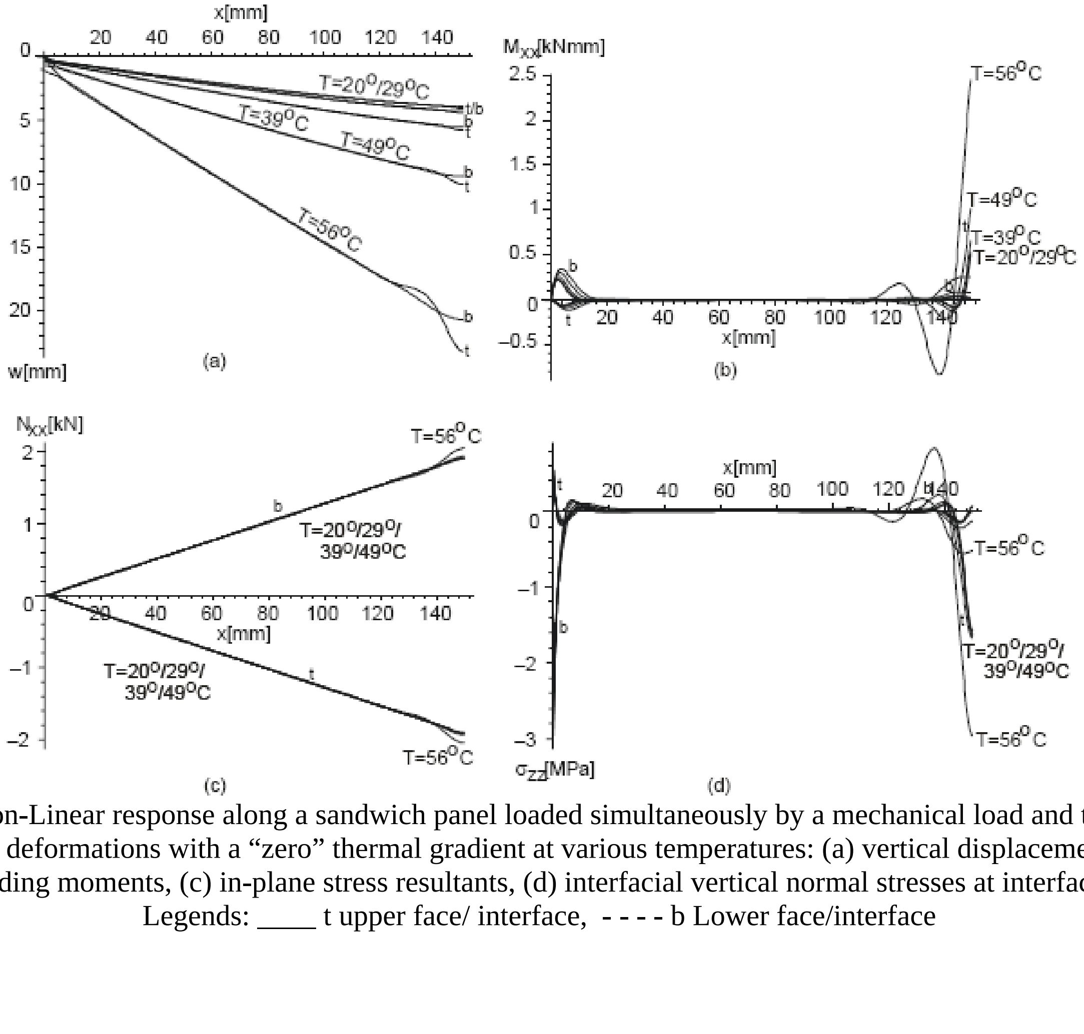

Fig. 4. Non-Linear response along a sandwich panel loaded simultaneously by a mechanical load and thermally induced deformations with a “zero” thermal gradient at various temperatures: (a) vertical displacements, (b) bending moments, (c) in-plane stress resultants, (d) interfacial vertical normal stresses at interfaces.
Legends: ____ t upper face/ interface, - - - - b Lower face/interface

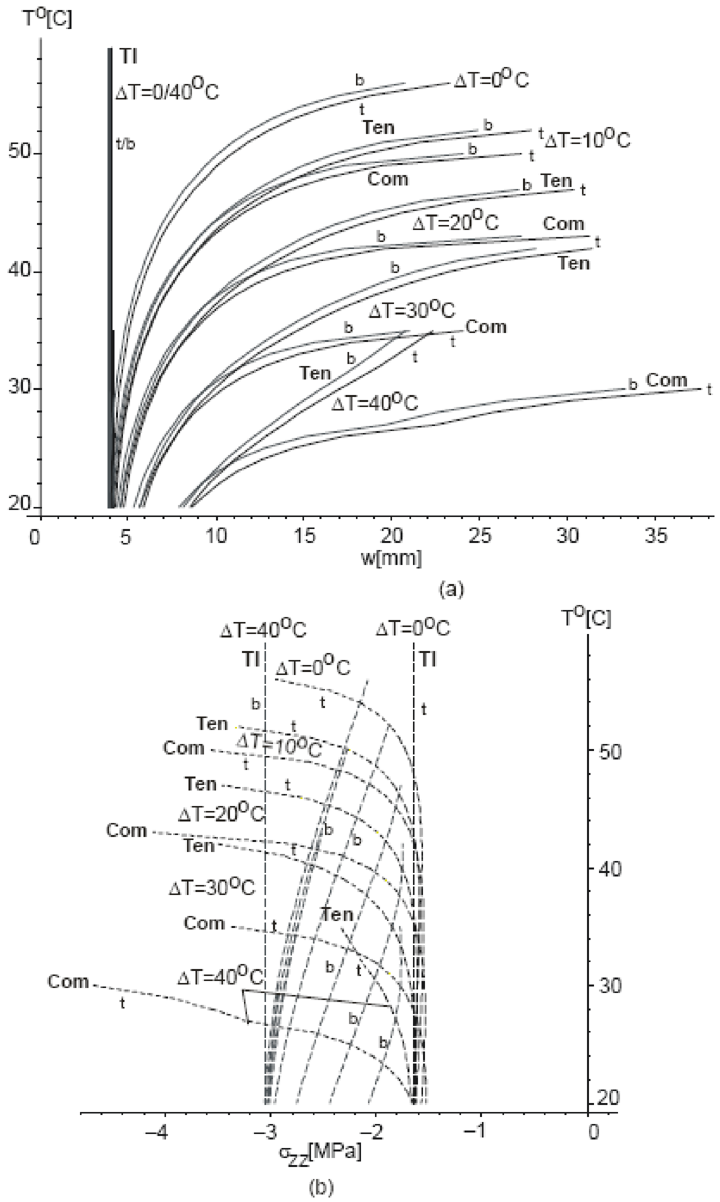

Fig. 5. Temperature equilibrium curves of maximum displacements and vertical normal stresses vs. temperature for an **unrestrained** sandwich panel loaded simultaneously with mechanical and thermal loads, with temperature-independent and temperature-dependent properties, at various thermal gradients where the elevated temperatures are imposed either on the tensile **(Ten)** or the compressed **(Com)** face sheet: (a) maximum vertical displacements, (b) maximum compressive interfacial vertical normal stresses at interfaces.
Legend: _________t upper face or interface, - - - - - -b Lower face or interface.

The sandwich panel is loaded in 3-point bending. The load is applied at the upper face sheet and the panel is supported only at its lower face sheet, while the edges of the core and upper face are free of tractions. The fixity of the panel is achieved by imposing longitudinal restraints on the edges of the faces, see Fig. 3a.

A thermal gradient is imposed within the core in two different ways, see Fig. 3a. In the first case the highest temperature is imposed at the lower tensile face (**Ten**), while in the second case the highest temperature is imposed at the upper compressed face (**Com**). The temperature-dependent core properties of the core are defined in Figs. 2b and 2c. The temperature gradient imposed through the core is 40°C. The solution procedure uses a parametric continuation approach with the temperature T as the parameter. The results are limited to a temperature of 79°C, which represents the upper limit of operating temperatures for this particular temperature-dependent DIAB core (HD80).

The deformed shapes of a sandwich panel, which is either longitudinally restrained or non-restrained at uniform (zero gradient through the core depth) temperatures of 79°C and 56°C, respectively, appear in Fig. 3b. The displacements for the unrestrained sandwich panel are much larger than for the restrained case. The indentation zone in the vicinity of the load is significant for the unrestrained deformation pattern, whereas it is almost invisible for the restrained case.

The results obtained for an unrestrained sandwich panel with a “zero” gradient through the core depth appears in Fig. 4 at five different temperature levels: 20°C, 29°C, 39°C, 49°C and 56°C. From Fig. 4a it is observed that an indentation occurs at mid-span for all temperature levels. Moreover, it is seen that the magnitude of the indentation increases with increasing temperature as a result of the degradation of the core properties. The mid-span displacement at the highest temperature (56°C) is about 2.5 times larger than the mid-span displacement corresponding to the temperature immediately below (49 C) as a result of the loss of stability see Fig. 4a.

From the bending moment diagrams, Fig. 4b, it is seen that large bending moments are present, which reach very high values at higher temperatures. The in-plane stress resultants of the face sheets appear in Fig. 4c, from which it is seen that fluctuations occur around mid-span only at high temperatures as a result of the large vertical displacements in this area. The in-plane stress resultants are nearly unaffected by the thermal loading. Finally, from Fig. 4d it is seen that very high interfacial vertical normal stresses are induced in the vicinities of the support and the mid-span at high temperatures as a result of the large displacements and the reduced rigidity of the core.

In Fig. 5, the equilibrium curves are presented for unrestrained sandwich panels for all thermal gradients. In addition, three different cases of thermal effects are presented. The first case represents a sandwich panel with temperature-independent (TI) core properties. The other two cases examine a core with temperature-dependent properties; one case where elevated temperatures are imposed at the tensile face sheets (**Ten**), and another where elevated temperatures are imposed at the face sheets loaded in compression **(Com)**.

The equilibrium curves of temperature vs. maximum vertical displacement appear in Fig. 5a. For the TI case it is seen that a thermal gradient exerts a minor effect on the response, which remains linear through the entire range of working temperatures. Unstable behaviour with very large displacements is seen for the TD cases for all thermal gradients at temperatures that lie well below the upper limit of operating temperatures.

For the “zero” thermal gradient case, denoted by ΔT=0°C, the instability starts around 55°C, and beyond 56°C the panel reaches extremely large displacements. The results reveal that when the tensile face sheet is warmer than the bottom face, loss of stability always occurs at a higher temperature then when the compressed face sheet is warmer. Notice, that at a thermal gradient of 40°C the case with a warmer tensile face sheet exhibits a stable non-linear behaviour, while the case where the compressed face sheet is warmer yields an unstable pattern with the probable existence of a limit point at a very low temperature. The same trends are observed for the maximum compressive interfacial vertical normal stresses, see Fig. 5b. In all cases, larger compressive stresses are observed when the compressed face sheet is warmer, and they reach very high values, which may exceed the compressive core strengths at the relevant temperatures.

5 Summary and Conclusions

The buckling studies for foam cored sandwich panels presented herein have in all cases demonstrated a significant reduction of the critical wrinkling temperature, as well as changes in the number of half-waves in the buckling pattern, when the temperature dependency (TD) of the core is accounted for.

Moreover, the interaction between mechanical loading and rising temperature at the tensile and compressive face sheets was studied numerically for unrestrained sandwich panels with and without a temperature-dependent core. For a temperature independent core, the results reveal that the response remains linear and constant through the entire range of working temperatures. Opposed to this, for the case of a temperature-dependent core, the response is unstable, and loss of stability occurs far below the upper operational temperature of the core. The case where the elevated temperature is imposed on the compressed face is even more severe, and loss of stability occurs at temperatures below those predicted for the case where the tensile face sheet is warmer.

Acknowledgements

The work presented was supported by:

- The Innovation Consortium "Integrated Design and Processing of Lightweight Composite and Sandwich Structures" - "KOMPOSAND" - funded by the Danish Ministry of Science, Technology and Innovation.
- US Navy, Office of Naval Research (ONR), Grant/Award No. N000140710227, under the "Solid Mechanics Program - Marine Composites and Sandwich Structures". The ONR program manager was Dr. Yapa Rajapakse.

References

[1] www.rohacell.com, *"WF Foam Data sheets"*, 2004.
[2] Divinycell, *"Data Sheet HD Grade"*, *Diab Group*, 2003.
[3] *"P and HP-Cores – Test Protocol"*, Diab Group, Private communications, 2005.
[4] Allen, H.G., *"Analysis and Design of Structural Sandwich Panels"*, London, Pergamon Press, 1969.
[5] Zenkert, D., *"An Introduction to Sandwich Construction"*, Chameleon Press Ltd., London, 1995.
[6] Mindlin, R. D. "Influence of transverse shear deformation on the bending of classical plates", *Transaction of ASME, Journal of Applied Mechanic*, 8, 1951, pp. 18-31.
[7] Reddy, J. N., *"Energy and Variational Methods in Applied Mechanics"*, John Wiley and Sons, Inc., New York, 1984.
[8] Tessler, A., Annett, M.S. and Gendron, G., "A {1,2}-order plate theory accounting for three dimensional thermoelastic deformations in thick composite and sandwich laminates", *Composite Structures*, 52, 2001, pp. 67-84.
[9] Liew, K.M., Yang, J. and Kitipornchai, S. "Laminated plates comprising functionally graded materials with temperature-dependent properties", *Journal of Applied Mechanics, Transaction of the ASME*, 71, 2004, pp. 839-850
[10] Chen, L.-W. and Chen L.-Y., "Thermal buckling behavior of laminated composite plates with temperature-dependent properties", *Composite Structures*, 13(4), 1989, pp. 275-287.
[11] Chen, L.-W. and Chen, L.-Y., "Thermal post buckling behavior of laminated composite plates with temperature-dependent properties", *Composite Structures* 19, 1991, pp. 267-283.
[12] Gu, P. and Asaro, R.J., "Structural buckling of polymer matrix composites due to reduced stiffness from fire damage", *Composite Structures*, 69, 2005, pp. 65-75.
[13] Birman, V., "Thermally induced bending and wrinkling in large aspect ratio sandwich panels", *Composites Part A: Applied Science and Manufacturing*, 36(10), October 2005, pp. 1412-1420
[14] Birman. V., Kardomateas, G.A., Simitses, G.J., Liu, L., "Response of a sandwich panel subject to fire or elevated temperature on one of the surfaces", *Composites Part A: Applied Science And Manufacturing* 37 (7), 2006, pp. 981-988.
[15] Liu, L.., Kardomateas, G.A., Birman, V., Holmses, J.W., Simitses, G.J., "Thermal buckling of a heat-exposed, axially restrained composite column", *Composites Part A: Applied Science And Manufacturing* 37 (7) 2006, pp. 972-980.
[16] Frostig, Y. "Hygrothermal (environmental) effects in high-order bending of sandwich beams with a flexible core and a discontinuous skin", *Composite Structures*, 37(2), 1997, pp. 205-221.
[17] Frostig, Y., Baruch, M., "Buckling of simply-supported sandwich beams with transversely flexible core - a high order theory", *Journal of ASCE, EM Division*, 119(3), 1993, pp. 476-495.
[18] Frostig, Y. "Buckling of sandwich panels with a transversely flexible core - high-order theory", *International Journal of Solids and Structures*, Vol. 35(3-4), 1998, pp. 183-204.
[19] Sokolinsky V., Frostig, Y., "Branching behavior in the non-linear response of sandwich panels with a transversely flexible core", *International Journal of Solids and Structures*, Vol. 37, 2000, pp. 5745-5772..
[20] Frostig Y. and Thomsen, O. T., Sheinman I., "On the Non-Linear High-Order Theory of Unidirectional Sandwich Panels with a Transversely Flexible Core", *International Journal of Solids and Structures*, Vol. 42 (5-6), 2005, pp. 1443-1463.
[21] Frostig Y. and Thomsen, O. T., "Thermal buckling and post-buckling of sandwich panels with a transversely flexible core", *International Journal of Solids and Structures* (In press).
[22] Frostig Y. and Thomsen, O. T., "Non-linear thermal response of sandwich panels with a transversely flexible core and temperature dependent mechanical properties", *Composites Part B: Engineering* (In press).
[23] Frostig, Y. and Thomsen, O.T., "Buckling and Non-Linear Response of Sandwich Panels with a Compliant Core and Temperature-Dependent Mechanical Properties", *Journal of Mechanics of Materials and Structures* (In press).
[24] Simitses, G J., *"An Introduction to the Elastic Stability of Structures"*, Prentice-Hall Inc., New Jersey, 1976.
[25] Stoer, J., Bulirsch, R., *"Introduction to Numerical Analysis"*, Springer, New York, 1980.
[26] Ascher, U., and Petzold, L., *"Computer Methods for Ordinary Differential Equations and Differential-Algebraic Equations"*, SIAM, Philadelphia, 1998.