2010

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Recommended Citation

Bahei-El-Din, Yehia; Shazly, Mostafa; El-Habbal, I.; and Elbahy, Y., "Modified sandwich structures for improved impact resistance of wind turbine blades" (2010). *Centre for Advanced Materials*. 10.
https://buescholar.bue.edu.eg/centre_advanced_materials/10

Proceedings of EWEC 2010
European Wind Energy Association Annual Conference
20-23 April 2010, Warsaw, Poland

MODIFIED SANDWICH STRUCTURES FOR IMPROVED IMPACT RESISTANCE OF WIND TURBINE BLADES

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ABSTRACT

Wind turbine blades are susceptible to damage due to fatigue as well as impact by flying objects and parts broken off failed blades of nearby wind towers. Localized, permanent compression of the foam core and delamination of the fibrous composite face sheets are typical damage modes and can lead to progressive structural failure. Sandwich structures modified by inclusion of flexible polyurethane (PU) layers within the cross section are examined under both impact and dynamic loads. Finite element models of sandwich structures with conventional and modified designs show that sandwich designs modified with PU interlayes exhibit reduced foam core crushing and the associated overall energy dissipation.

1. INTRODUCTION

Standard sandwich designs, which consist of laminated face sheets bonded to structural foam core often exhibit collapse of the core under both quasi static and dynamic, compressive loads. Collapse of the foam is usually accompanied by delamination of the face sheet when bending moments are dominant [1]. Under lateral impact and blast loads, induced compression waves propagate through thickness of the sandwich structure and cause permanent compression of the foam core [2]. Recent work by Dvorak and Suvorov [3-5] and Bahei-El-Din et al. [6-8] showed that permanent compression of the foam core can be partially suppressed if a thin membrane of a flexible material is inserted between the face sheet and the core on the loading side. Various types of materials were investigated for the proposed membrane including polyurethane, polyurea, elastomeric foam and their combinations.

The present work extends this approach to sandwich structures for end application in wind turbine blades. Materials acquired for this particular application are tested and properties are utilized in a finite element simulation using ABAQUS [9] for two problems; one examines the effect of polyurethane (PUR) on protecting the foam material against crushing under impact loading, and one examines free vibrations of sandwich beams with designs modified with PUR interlayers. The overall response is computed in terms of stress-strain behavior and displacement and energy histories in order to quantify the extent of protection provided by the addition of PUR interlayers in the sandwich design. Other parameters considered in the analysis include the thickness of the PUR interlayer and the incident velocity of impact.

The paper first outlines in Section 2 the geometry of the sandwich construction considered and the properties of the materials utilized. Section 3 details the impact problem for a foam specimen protected by PUR and Section 4 presents free vibrations of a sandwich beam with conventional and modified designs. Conclusions are given in section 5.

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2. GEOMETRY AND MATERIAL PROPERTIES

Conventionally designed sandwich plates consist of laminated fibrous composite face sheets bonded to closed cell structural foam core, Fig. 1a. The modified sandwich design, on the other hand, inserts a polyurethane (PUR) interlayer between the face sheet and the foam core on one side where the load is expected, Fig. 1b.

The face sheets are E-glass/epoxy composite laminates. Mechanical properties of a unidirectional ply are given in Table 1 as Mori-Tanaka estimates [10] for fiber volume fraction of 40%. Here, E is the elastic Young's modulus, G is the elastic shear modulus and ν is Poisson's ratio. The reference coordinate system is such that X_1 coincides with the fiber longitudinal direction, and X_2-X_3 is the transverse plane. Behavior of the composite material is assumed to be linear elastic.

The core material is closed cell structural foam. Samples with a density of 100 g/cm^3 were provided by AIREX and tested under compression. The measured quasi-static behaviour is given in Fig. 2a. The response is linearly elastic up to the yield stress of 2.0 MPa and is followed by perfectly plastic response up to about 50% strain. Increasing the strain beyond this magnitude initiates locking of the foam closed cells, which causes a sharp increase in the compression load. Full densification of the foam is reached at strain of about 85%.

The polyurethane (PUR) is a nearly incompressible rubber like material. Samples measuring 12 mm in diameter and 6 mm in thickness were provided by Bakir Plastics of Egypt and tested under uniaxial, strain-controlled compression at 0.1/s. The measured stress-strain response is shown in Fig. 2b. The loading branch of the stress-strain curve is slightly nonlinear. On unloading, the stress-strain response is nonlinear with a large hysteresis forming before the specimen is fully unloaded. It is worth noting that the hysteresis generated by the loading/unloading cycle does not appear when the contact between the upper and lower surfaces of specimen and the loading platens is made frictionless by means of a lubricant.

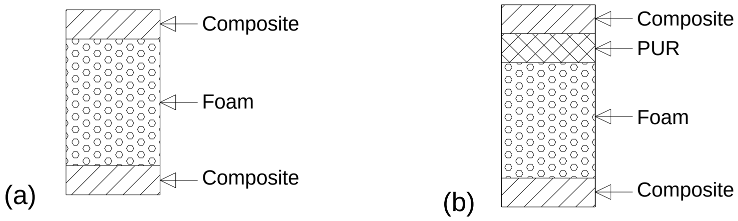

Fig. 1. Sandwich construction, (a) Conventional design, (b) Modified design.

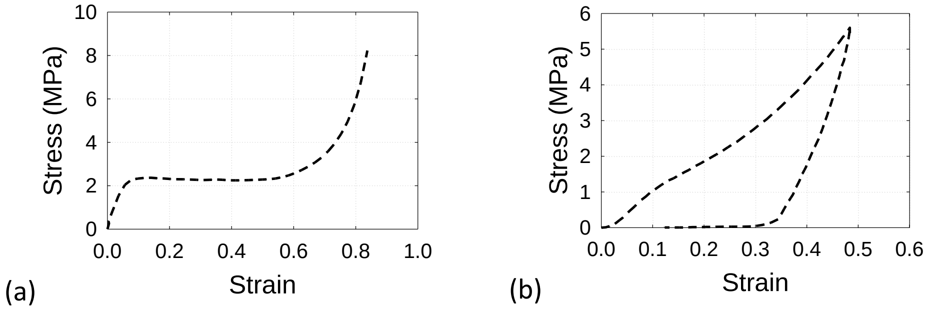

Fig. 2. Measured response under uniaxial compression, (a) closed cell foam, (b) PUR.

Table 1. Mechanical properties of E-glass/epoxy unidirectional composites.

ρ (kg/m^3)	E_1 (GPa)	$E_2 = E_3$ (GPa)	$G_{12} = G_{13}$ (GPa)	G_{23} (GPa)	$\nu_{12} = \nu_{13}$	ν_{23}
1600	32.3	7.74	2.81	2.92	0.252	0.379

Table 2. Parameters of crushable foam material model.

ρ (kg/m^3)	Young's Modulus (MPa)	Poisson's ratio	Uniaxial yield stress (MPa)	Compression yield stress ratio[1]	Hydrostatic yield stress ratio[2]
100	111	0.1	2.0	1.0	0.05

[1] Yield stress under uniaxial compression / Yield stress under hydrostatic compression.
[2] Yield stress under hydrostatic tension / Yield stress under hydrostatic compression.

Table 3. Parameters of PUR material model (Eq. 1).

ρ_o (kg/m^3)	C_o (m/s)	s	Γ_o
1200	250	2.0	1.5

Closed cell foam is modelled as crushable foam with the stress-strain response shown in Fig. 2a. Additional material parameters required by this model are listed in Table 2.

Pending a more complete experimental evaluation of the PUR, the material behavior was simulated by an elastic-plastic hydrodynamic model as proposed by Bahei-El-Din et al. [6]. In this case, the yield stress is pressure dependent, and the pressure generated is provided by Mie-Gruneisen equation of state as

$$p = \frac{\rho_o C_o^2 \eta (1 - \Gamma_o \eta/2)}{(1 - s\eta)^2} + \Gamma_o \rho_o E_m \tag{1}$$

where ρ_o and ρ are the reference and current densities of the material, and $\eta = 1 - \rho_o/\rho$ is the nominal volumetric compressive strain. Parameters C_o and s define the linear relationship between the shock velocity U_s and the particle velocity U_p as $U_s = C_o + sU_p$, Γ_o is a material constant and E_m internal energy density. Table 3 lists the above parameters, which were determined by fitting the loading branch of the stress-strain response shown in Fig. 2b.

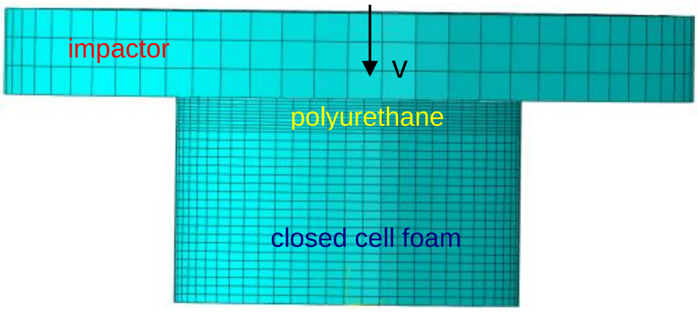

Fig. 3. Finite element model of impact problem.

3. LOW VELOCITY IMPACT PROBLEM

The effect of PUR layer on improving the impact resistance of sandwich structures, especially in reducing crushing of the foam core was investigated. Figure 3 shows the finite element model of a closed cell foam specimen covered with a layer of PUR, which is subjected to impact by a steel impactor moving at a velocity v. The impact velocity varied from 2 m/s to 13 m/s. The foam specimen measures 20 mm in diameter and 10 mm in height. Various thicknesses of the PUR layer were examined starting from 0.5 mm up to 10 mm. A refined mesh was selected in direction of the induced compression with 20 elements in the foam and 5 elements per mm in the PUR. Eight-node brick elements with reduced integration were used. ABAQUS explicit finite element analysis with large deformations was applied. The boundary conditions consisted of axial constrains at the base of the foam specimen, and hard contact was applied to model contact between the specimen and the impactor in the normal direction. Frictionless contact was applied in the tangential direction of the contact surfaces.

The extent of the protection provided by the PU layer for the foam specimen under impact is illustrated in Figs. 4 and 5. In Fig. 4, the stress-strain response of the foam specimen is plotted for several magnitudes of the impact velocity v. For comparison, the results for a foam specimen without PUR cover are shown along side with those of a foam specimen protected by a PUR layer with various thicknesses. The stress and strain represent the overall true rather than engineering values, where the stress is found from the reactions at the constrained nodes at the bottom surface of the foam specimen, and the strain is computed from the displacement at its top surface.

It is seen that the foam without PUR cover sustains permanent crushing at impact velocity as small as 2 m/s, Fig. 4a. As indicated by the strain magnitudes, the crushed volume of the unprotected foam increases substantially as the impact velocity increases. At v = 13 m/s, Fig. 4d, the foam specimen is crushed down to about 20% of its height. Adding PUR at the top of the foam specimen eliminated crushing of the foam completely at impact velocity of 2 m/s and led to a significant reduction of the foam compression at higher velocities. As the thickness of the protecting PUR layer increases, the peak stress of the foam sample decreases and thus the compressive strain of the foam decreases.

At v = 5 m/s, Fig. 4b, PUR layers of thicknesses up to 4 mm did not prevent crushing of the foam specimen. A reduction in the foam strain on the order of 50% and 75 % is seen if the PUR thickness is 2 mm and 4 mm, respectively. PUR thicknesses greater than 4 mm kept the foam set entirely in the elastic zone. At impact velocity of 10 m/s on the other hand, Fig. 4c, none of the PUR thicknesses investigated prevented crushing of the foam specimen. As expected, however, thicker PUR layers led to less damage in the foam. For example, protection of the foam specimen with a 10 mm thick PUR layer reduced strain of the foam specimen by over 50%, from 0.47 to 0.22.

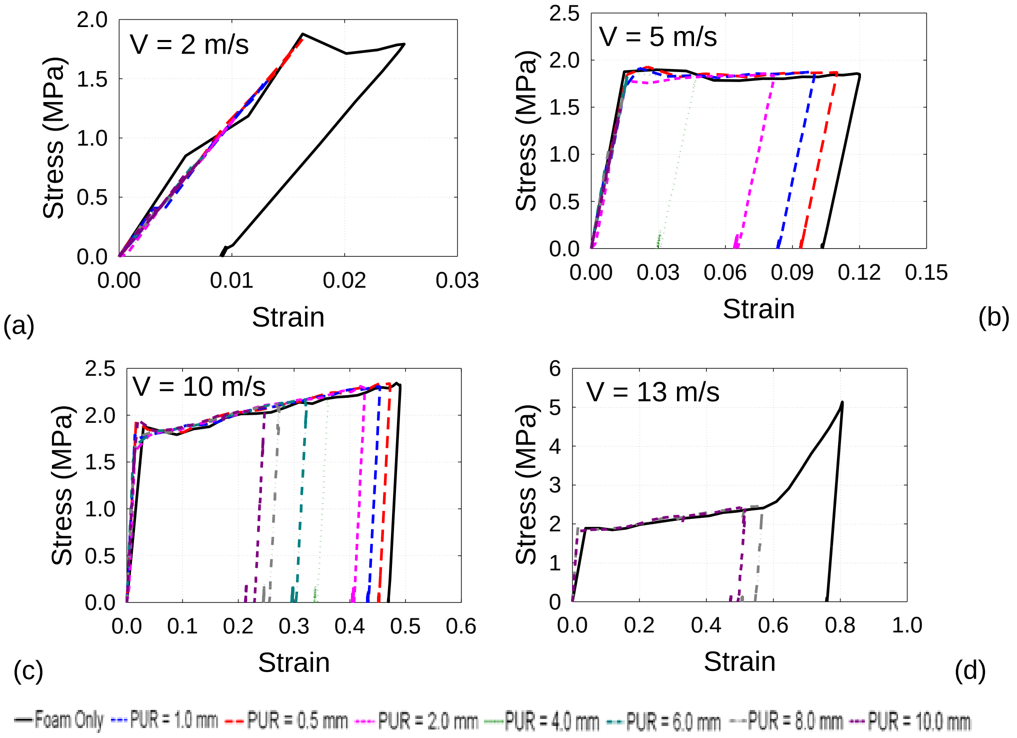

Fig. 4. Computed response of closed cell foam specimen due to impact.

Increasing the impact velocity to 13 m/s encountered numerical difficulties due to excessive deformations of both the foam and the PUR. This improved for large PUR thicknesses. Only PUR thicknesses of 8 and 10 mm were able to sustain this impact velocity, Fig. 4d. Results for the unprotected foam show crushing of a very large volume of the specimen with a large strain of about 80%. This was decreased by 44% when the foam was protected by a 10 mm thick PUR layer.

Figure 5 shows time histories of the internal energy density of the closed cell foam specimen. The energy dissipated by permanent deformation of the foam is the magnitude at the plateau of the curves in Fig. 5. As expected, larger impact velocities lead to larger energy dissipation. Placement of a PUR layer at the top of the foam protected the foam crushing as evident from the reduced energy dissipation. Increasing the PUR thickness reduces the dissipated energy in the foam. For example, energy dissipation almost vanished for impact velocity of 2 m/s and PUR thickness of 10 mm, Fig. 5a.

4. FREE VIBRATION PROBLEM

In this problem, the change in free vibration characteristics of a sandwich beam modified by a PUR interlayer is examined. The reference model (A), Fig. 6, has a conventional sandwich design consisting of a 10 mm thick foam core and a composite face sheet bonded on either side. The composite face sheet is E-glass/epoxy, (0/90)/(0/±45) fibrous laminate with a total thickness of 2.03 mm. Using Owens Corning composites, each ply of the biaxial (0/90) laminate is taken as 0.43 mm thick. On the other hand, thickness of the 0^o ply in the triaxial laminate is 0.57 mm thick, and that of each of the 45^o plies is 0.3 mm. Table 1 lists mechanical properties of an individual ply.

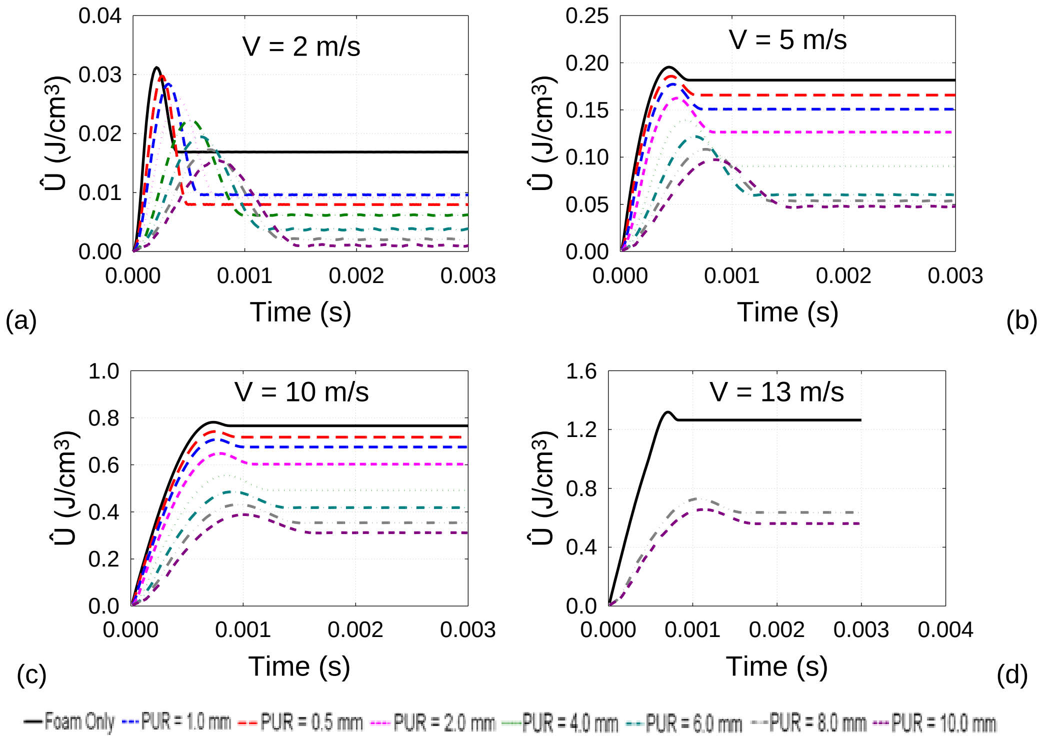

Fig. 5. Internal energy density $\hat{U}$ in closed foam cell specimen due to impact.

In the modified model (B), the composite beam is identical with that of model (A), however a 2 mm thick PUR interlayer was inserted between the top face sheet and the foam core. The finite element mesh is shown in Fig. 7. Eight-node brick elements were utilized in order to accommodate the foam, PUR, and orthotropic composite material models. However, displacement boundary conditions which enforce plane strain deformations in the width direction of the beam were applied.

The beams shown in Fig. 6 were subjected to a downward tip displacement as shown in Fig. 7. After the displacement was forced to 1.6 mm, it was released and the free vibration displacement was computed for a period of 30 seconds together with the internal energy density at equal time intervals of 0.001 s.

Figure 8 shows time histories of the displacement at the beam tip for the standard sandwich beam (A), and the PUR-modified sandwich beam (B). The results indicate that the PUR interlayer leads to a significant reduction in permanent compression of the foam core. The mean displacement at the tip of the beam was reduced by over 50% from 1.25 mm to 0.6 mm. Inclusion of the PUR interlayer in the sandwich design, however, increased the displacement amplitude in comparison with the conventional design. There is also clearly a change in the beam frequency. We note that structural damping was not introduced in these models in order to determine the effect of the mechanical properties of the PUR layer alone on the free vibration response of the beam. While the benefits of PUR interlayers on partially suppressing crushing of the foam core are clear, their effect on overall damping and natural frequencies remain to be investigated.

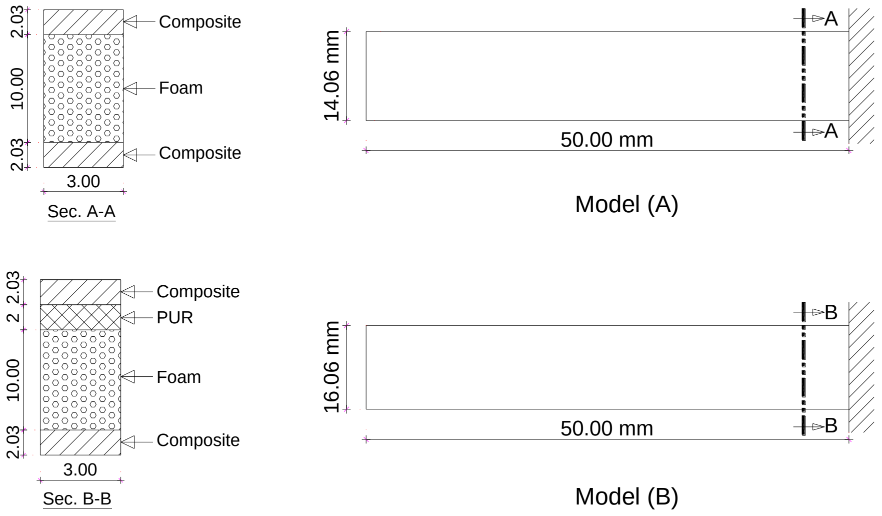

Fig. 6. Geometry of sandwich cantilever beams.

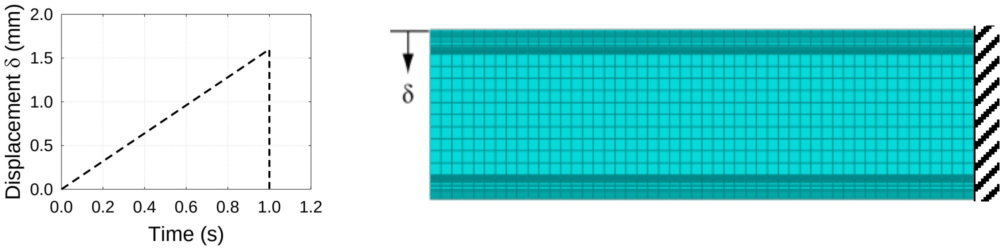

Fig. 7. Applied tip displacement.

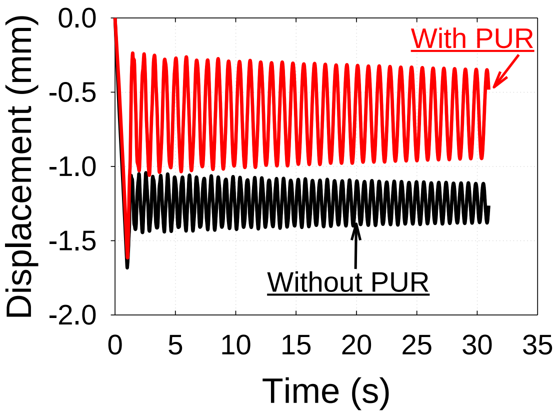

Fig. 8. Free vibration response of sandwich beams.

5. CONCLUSIONS

With end application in wind turbine blades in mind, the present research investigated modifying conventional sandwich designs by adding polyurethane interlayers in order to improve their response to impact and dynamic loads. To this end, two problems were studied, one examines the protection of closed cell foam, which is used as core material against low velocity impact, and one examines free vibrations of sandwich beams. Material models, guided by experimental measurements, and finite element modelling were applied.

The following salient results summarize our findings:

1) A PUR layer generally provides protection to the closed cell foam material from crushing under dynamic loads at various degrees, which depend on the layer thickness.
2) For specific impact velocities and PUR thickness, it is possible to totally suppress crushing of the foam core.
3) Although the foam may sustain partial crushing at some higher impact velocities, thickness of the PUR may be optimized to avoid complete foam locking and preserve structural integrity.
4) Using a PUR interlayer between the foam core and the composite face sheet improved the free vibration response of a cantilever sandwich beam by reducing the permanent displacements caused by foam crushing.
5) Analysis of the effect of PUR interlayer on damping, natural frequencies, fatigue, etc. of sandwich beams subjected to dynamic loading is beyond the scope of this paper and remains to be fully examined.

ACKNOWLEDGEMENT

This work was performed under research grant number MED/2008/172-215 from the European Commission through EU-Egypt Innovation Fund. Research, Development and Innovation Program of the Ministry of Higher Education and Scientific Research, Egypt served as project monitor and Y. Bahei-El-Din served as the Principal Investigator.

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