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Dynamic response of composites sandwich plates with carbon nanotubes subjected to blast loading

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ABSTRACT

An experimental study of the dynamic response of composite aluminum epoxy resin–CNT sandwich plates subjected to blast load is presented in this paper. The sandwich plates consist of aluminum square plates with a core of epoxy resin matrix and 5% in weight of CNT. For comparison purposes, plates with neat epoxy resin core were also tested. Disc shaped plastic explosive (PE4) is used to impart uniform and localized blast loading to the plates. The mass of the explosive is varied to provide a range of response of the sandwich panels from plastic deformation to complete tearing. It was found that the permanent displacement is larger for the plates with CNTs, as for uniform well as localized blast loading, indicating that the inherent brittleness of epoxy resins was overcome by adding CNTs. On the other hand, once the composite material with CNTs has reached the fracture, it is exhibited better energy dissipation behavior than the neat epoxy specimens. Preliminary results show that the failure load is larger for the specimens with CNTs.

1. Introduction

Blasting loads have come to be forefront of attention in recent years due to a number of accidental and intentional events that affected important structures all over the world, clearly indicating that this issue is important for purposes of structural design and reliability analysis. In consequence, extensive research activities in the field of blast loads have taken place in the last few decades, including the research of composites materials for reinforcement of structural elements of armors, vehicles, etc.

Since their discovery in 1991, many interesting properties of carbon nanotubes (CNTs) have been reported by several researchers. One such promising application is CNT-based reinforced composites. The exceptional mechanical and physical properties demonstrated for carbon nanotubes, combined with their low density, make this new form of carbon an excellent candidate for composite reinforcement [1]. CNTs have been observed to drastically change the mechanical properties of polymer composites [2,3]. On the other hand, epoxy resin is a cross linked polymer widely used as a matrix for advanced composites given its good stiffness, specific strength, dimensional stability and chemical resistance. The main drawback of epoxy resins for structural applications may be its inherent brittleness which could be partially overcome by adding CNTs.

The critical aspects for the progress and industrialization of a nanocomposite are: dispersion of the nanoreinforcement filler within the matrix and a strong interfacial bonding between the reinforcement element and the matrix. Functionalized carbon nanotubes have the potential to be more efficient as reinforcing agents than pristine CNTs, for the following reasons: (i) functionalized nanotubes should lead to stable and uniform dispersions in organic solvents and (ii) functional groups attached to the surface of CNTs should react with the epoxy matrix during the curing process, and build covalently linkage [4,5].

Hernandez Perez et al. [6] studied the mechanical properties of an epoxy/CNT composite with two aspect ratio nanotubes showing that while tensile properties presented very limited improvement, the impact resistance and fracture toughness of the nanocomposites were significantly improved. Yeh and Hsieh [7] investigated the dynamic properties of sandwich beams with multi-walled carbon nanotubes (MWCNTs)/polymer nanocomposites as core materials demonstrating that the face plates dominated the stiffness of the sandwich beams while the core materials dominated the damping characteristics of the sandwich structure.

On the other hand, the response of fully clamped metal plates subjected to uniform and localized blast loads has been studied for many years by Nurick [8,9]. Failure of circular plates subjected to uniform blast loads is characterized by a permanent midpoint deflection increased with increasing impulse resulting in thinning

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at the boundary [10]. Under localized blast loads an inner dome superimposed on a larger global dome is observed. At higher impulses, thinning at the central area and boundary of the plate occurred and finally tearing in the central area was observed [11,12]. Finally, Jacinto et al. [13] presented a comparison between testing and numerical responses of metallic plates subjected to explosive loads, in order to obtain guides to the numerical modeling and analysis of this phenomenon.

Regarding the use of CNTs in composite materials for structural strengthening under blast loads, Reda Taha et al. [14] presented a numerical approach for design of composite laminates for enhanced blast resistance using CNTs and developed an optimization approach based on determining the optimal CNT content in the composite interface. Grujicic et al. [15] developed a numerical model which allows the study of the effect of MWCNTs as reinforcement of armors, obtaining that the use of MWCNT reinforcements aligned orthogonally to the armor faces may be more beneficial to the improvement of the armor's ballistic-protection performance. Recently, Altunc et al. [16] suggested a systematic reliability-based design approach to compute the probability of failure of a composite laminated.

Tekalur et al. [17] used a shock tube and a controlled explosion tube to study the dynamic damage behavior of E-glass and carbon fiber composite materials but, in the authors' best knowledge; there is no evidence of experimental works with composite materials with CNTs under blast loads.

In this paper, a composite material for reinforcement of structural elements under blast loading is presented. The material is composed of aluminum, CNTs and epoxy. Tests under blast loads of composite plates were made to study the mechanical properties and the dynamical behavior of this composite material.

2. Materials and methods

2.1. Materials

Carboxil MWCNTs were obtained from Chengdu Organic Chemicals and Co. (www.timesnano.com). The nanotubes had an external diameter of 20–30 nm and a length of 0.5–2 μm. According with his manufacturer, the nanotubes have purity over the 95%. The nanotubes were utilized as received from the manufacturer. The epoxy resin used was Epokukdo YD-128 and the curing agent was an aromatic amine modified Docure TH-430 (www.kukdo.com). Two types of aluminum, Al 1050 for uniform blast loads and Al 2040-T3 for localized blast load were used.

2.2. Preparation of nanocomposites and neat resin specimens

First, aluminum square plates of 150 mm of side were prepared. The plates were sand blasted to improve the adherence with the epoxy and put into moulds. Nanocomposites were prepared using 5% wt of CNTs. The epoxy resin was heated at 70 °C to prevent bubbles. Carbon nanotubes were added and mixed manually at macroscopic level for 10 min. For some samples, a magnetic stirrer was used to mix the parts but the obtained results were similar to manual mixing. After that, the curing agent was added to the epoxy/CNT and mixed for 10 min at 70 °C. The mixing ratio was one part of epoxy by 0.6 parts of curing agent.

Two types of composites plates were made. The first one has a one side aluminum plate and the second one is a sandwich plate. In the first type, the mixture was cast into the moulds and cured at room temperature. In sandwich plates, a portion of the mixture was cast into the moulds and cured for 5 h at room temperature. Then, the remaining mixture was added until achieve the thickness wanted and cured at room temperature. In these conditions the maximum strength is reached to seven days. For comparison purposes, neat epoxy composites were made with the same procedure.

For uniform blast test 24 specimens were made (Fig. 1). The sandwich plates were made of plates of 1 mm thickness of aluminum Al 1050 and an epoxy core (epoxy/CNT) of 2 mm. The one side aluminum plates were tested in pairs to reach a 4 mm core. For localized blast test 32 specimens were made (Fig. 2). In one case, two plates of 1 mm thickness of aluminum Al 2024 were added to the sandwich plates. In the other case, two sandwich plates were tested together.

Small samples of pure epoxy and epoxy/CNT were observed with a scanning electronic microscope (SEM) (Figs. 3 and 4). The composite containing CNTs exhibits a significantly rougher fracture surface compared to the neat epoxy, indicating a toughening effect of the nanotubes.

The plates of 2 mm core (Fig. 1) have an accuracy in the size of ±0.106 mm and a coefficient of variation (COV) of 4.44%. The plates of 4 mm core have an accuracy of ±0.227 mm and a COV of 5.30%. Similar results are found for specimens subjected to localized blast test (Fig. 2).

Although the size of the core of the specimens has a direct influence on the results; considering the nature of the physical problem and the other uncertainties involved (weight of the explosive load, measurement of the impulse, etc.), the accuracy in the size of the specimens can be considered reasonable.

3. Experimental procedure

Disc shaped plastic explosive PE4 of radius R_0 and thickness h is used to impart a blast load onto the loaded side of test plates. The impulse is measured using a ballistic pendulum.

3.1. Ballistic pendulum

The ballistic pendulum (Fig. 5) was used to measure the impulse applied to the test plate. The ballistic pendulum consists of a steel I-beam suspended on four spring steel cables. The spring

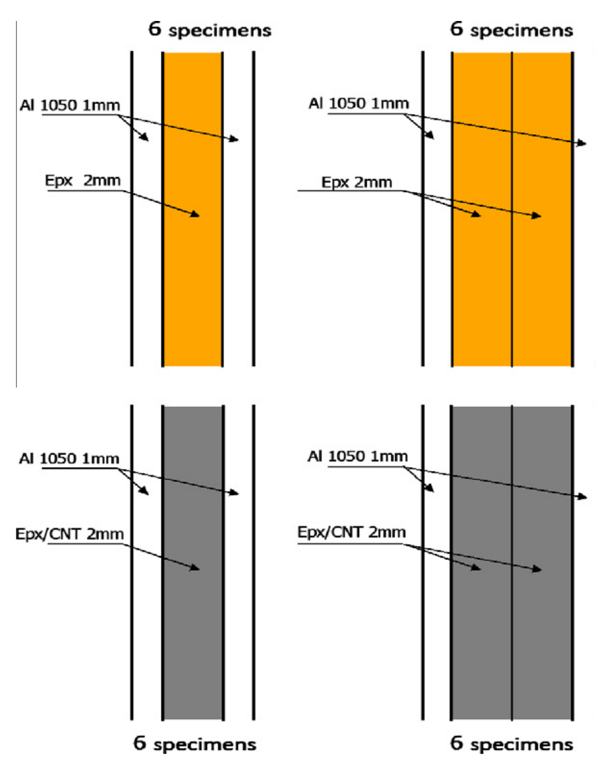

Fig. 1. Specimens for uniform blast test.

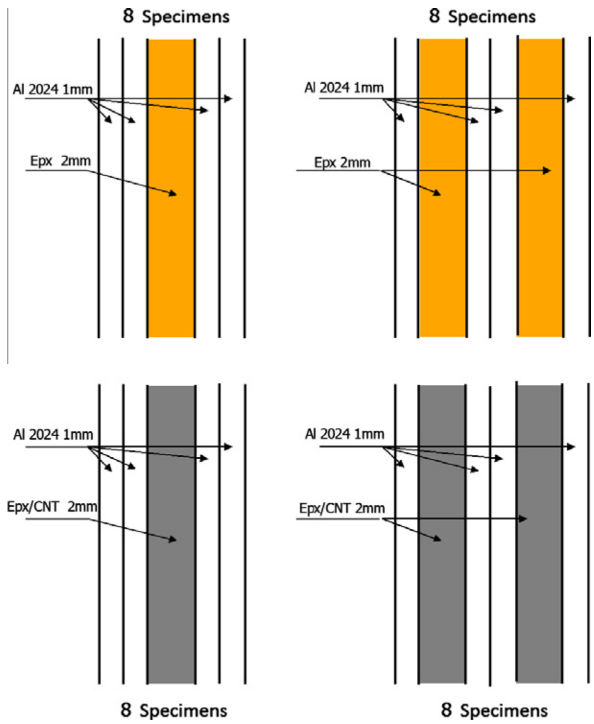

Fig. 2. Specimens for localized blast test.

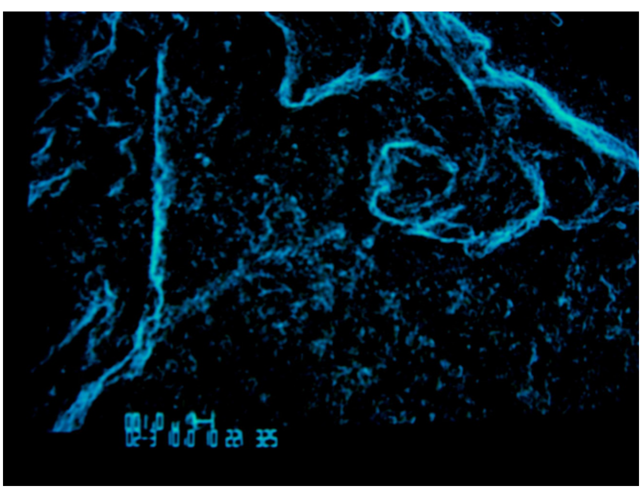

Fig. 3. SEM image of the fracture surface in pure epoxy resin.

steel cables are attached to the I-beam of the ballistic pendulum by four adjustable screws. The pendulum is leveled by adjusting the screws and verified using a spirit-level. Counter balancing masses are attached at one end and they are used to counter the mass of the test rig attached on the other end so as to ensure that all four spring steel cables carry the same load. Hence, the impulse generated by the explosion is transmitted through the centroid of the pendulum. A soft tipped recording pen is attached to the pendulum on the same side as the counter balancing masses, to record the oscillation amplitudes of the pendulum on a sheet tracing paper. The oscillation relates directly to the impulse generated by the explosion and transmitted to the test specimen (see Appendix A).

3.2. Test rig

The test rig consists of two (244 mm × 244 mm) clamping frames made from 20 mm thick mild steel. In the uniform blast

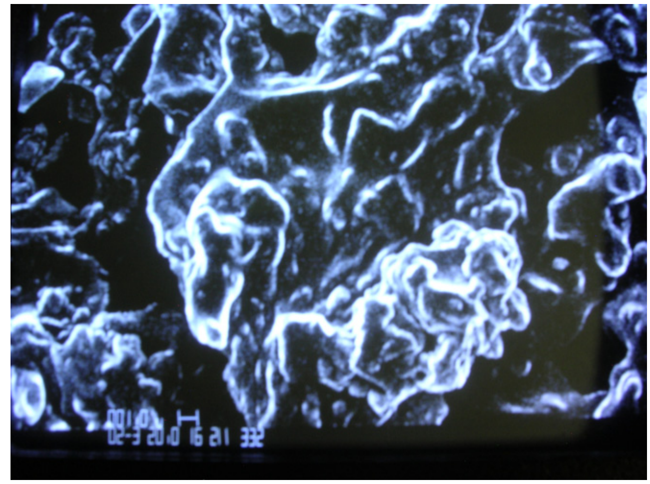

Fig. 4. SEM image of the fracture surface in epoxy/CNT.

Fig. 5. Ballistic pendulum.

test, a tube of required length is screwed onto one of the clamping plates and the other clamping plate has a hole machined to 90 mm diameter, the same as the internal diameter of the tube. The test specimen is sandwiched between the two clamping plates (Fig. 6).

The test rig is attached to the ballistic pendulum using four connecting spacer rods. The spacer rods allow the plate to deform without coming in contact with de I-beam of the ballistic pendulum.

3.3. Blast loading

Plastic explosive PE4 is used to provide the blast load on test specimens. PE4 is a combination of RDX and Lithium grease [18]. The physical characteristics of the explosive are presented in Table 1.

The PE4 is shaped into a disc of diameter 10 mm or 20 mm and placed onto a 13 mm thick polystyrene pad as shown in Fig. 7. The polystyrene blast platform does not affect the explosive load as its density is very low, and post test inspections shows that the polystyrene has been burnt up.

The mass of the explosive was varied to provide a range of response of the sandwich panels from deformation to complete tearing. Considering the facilities of the laboratory and the mass for breaking the plates, a mass of explosive between 1.5 and 3 g of

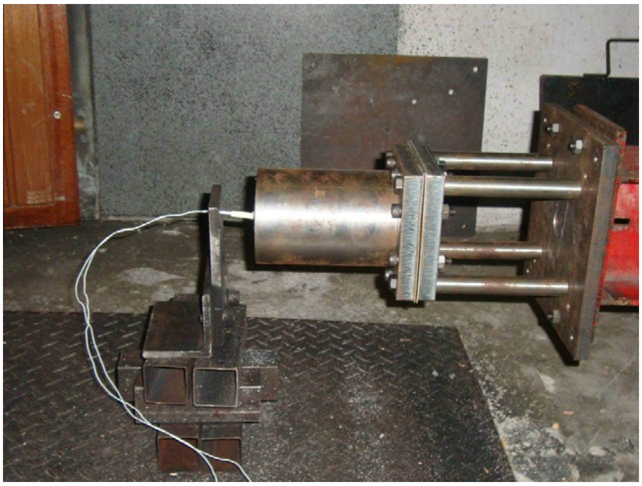

Fig. 6. Test rig.

Table 1
Explosive properties.

RDX and Lithium grease	88% RDX and 12% Lithium grease
Density	1.6 g/cm^3
TNT equivalent	130% (by ballistic mortar tests)
Detonations velocity	8200 m/s

Fig. 7. Polystyrene blast platform.

PE4 was used for the case of uniform blast tests and a mass of explosive between 3 and 5 g of PE4 was used for localized blast tests.

The diameter of the pad is identical to the diameter of the recess machined at end of the tubes (90 mm). A 1 g leader of explosive is usually used to attach the detonator to the main charge. The detonator was attached to the explosive and activated remotely.

3.4. Blast loading condition

The plastic explosive was attached to a 13 mm thick polystyrene pad using a strip of double sided tape and the pad was pushed into place on the end of a tube. In the uniform blast test, a standoff distance was maintained constant and equal to the length tube (180 mm) and no leader explosive was used. In the localized blast test, the polystyrene pad is placed directly on the specimens.

3.5. Failure modes of thin plates subjected to blast loads

The failure modes for circular plates subjected to uniform blast loads were observed by Teeling-Smith and Nurick [11]. The different modes of failure were defined as: large inelastic deformation of the plate (Mode I), tearing (tensile failure) at the supports (Mode II) and transverse shear failure at the supports (Mode III), observed in thick plates.

4. Testing and results

The thickness and mass of each plate were measured before the tests and the midpoint deflection was measured with a digital caliber after the tests. The impulse was obtained with the oscillation amplitudes of the pendulum as described in Section 3.1. In Tables 2–5, the term mass is the total mass of explosive, I is impulse, δ is the midpoint deflection, t is the total thickness of the plates and δ/t is the midpoint deflection/thickness ratio.

4.1. Uniform blast tests

Mode I type failure was observed. As expected, midpoint deflection increased with increasing impulse. The plate profile resembled a uniform dome shape (Fig. 8).

4.1.1. Sandwich plates of 2 mm core

The results of sandwich plates of 2 mm core are presented in Table 2. The average impulse was similar for the epoxy/CNT and pure epoxy plates but the average deflection/thickness ratio was 15% larger for the epoxy/CNT plates.

4.1.2. Sandwich plates of 4 mm core

The one side aluminum plates were tested back to back reaching 4 mm of core thickness. Results are presented in Table 3 and Figs. 9 and 10. For the same amount of charge explosive, the epoxy/CNT plates had higher deflections than the pure epoxy plates. The average deflection/thickness ratio was 22% larger for epoxy/CNT plates.

Table 2
Experimental results for sandwich plates of 2 mm core.

Epoxy core 2 mm					Epoxy/CNT core 2 mm				
Specimen	Mass (g)	I (Ns)	δ (mm)	δ/t	Specimen	Mass (g)	I (Ns)	δ (mm)	δ/t
25	1.50	3.66	4.53	1.02	42	1.50	3.24	4.70	1.08
					46	1.50	3.03	2.90	0.66
27	2.00	4.04	7.91	1.88	41	2.00	5.44	12.16	2.76
24	2.25	5.14	8.26	1.97	43				
						2.50	6.10	12.71	2.86
23	2.75	6.67	9.93	2.23	45				
						3.00	7.42	13.92	2.90

Table 3
Experimental results for sandwich plates of 4 mm core.

Epoxy core 4 mm					Epoxy/CNT core 4 mm				
Specimen	Mass (g)	*I* (Ns)	*δ* (mm)	*δ*/*t*	Specimen	Mass (g)	*I* (Ns)	*δ* (mm)	*δ*/*t*
6–8	2.00	4.77	7.16	1.13	30–31	2.00	4.48	9.12	1.45
					36–38	2.25	5.08	8.10	1.34
14–15	2.50	5.82	10.60	1.66	29–37	2.50	6.98	12.72	2.19
16–22	2.80	5.48	8.05	1.24	32–33	2.80	7.35	12.61	1.97
9–10	3.00	6.86	10.60	1.64					

Table 4
Experimental results for sandwich plates of 2 mm core + 2Al.

Epoxy 2 mm core + 2Al				Epoxy/CNT 2 mm core + 2Al			
Specimen	Mass (g)	*I* (Ns)	*δ* (mm)	Specimen	Mass (g)	*I* (Ns)	*δ* (mm)
18	3.00	7.18	12.08	25	3.00	5.76	11.42
21	3.50	7.62	13.17				
19	4.00	7.65	–	26	4.00	6.77	16.42
20	4.00	8.50	–	40	4.00	7.32	–
23	4.00	8.99	–				
				39	4.25	7.71	–
				38	4.5	8.09	–
				27	5.00	8.97	–

Table 5
Experimental results for two sandwich plates.

Two epoxy sandwich plates				Two epoxy/CNT sandwich plates			
Specimen	Mass (g)	*I* (Ns)	*δ* (mm)	Specimen	Mass (g)	*I* (Ns)	*δ* (mm)
10–11	3.00	8.40	14.00				
12–13	3.50	6.08	15.55				
14–15	4.00	7.26	13.76	36–37	4.00	7.65	14.26
8–9	4.00	8.61	–				
16–17	4.50	5.93	–	41–42	4.50	8.83	17.27
				43–44	4.7	8.90	17.75
				34–35	5.0	9.63	–

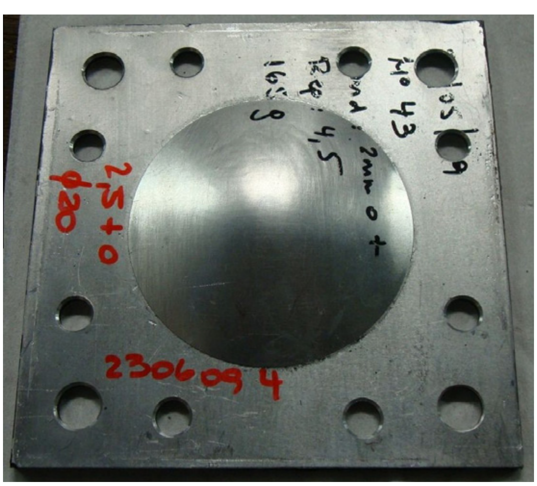

Fig. 8. Midpoint deflection.

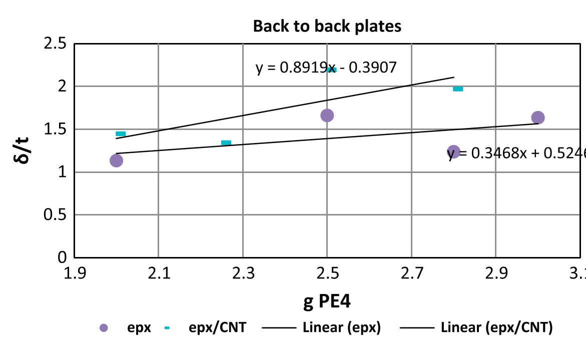

Fig. 9. Dynamic response vs. weight of the explosive. 4 mm core plates. Uniform loading.

These specimens allowed observing the fracture patterns of the core (Figs. 11 and 12). For this purpose, two plates with similar deflections were compared. The neat epoxy resin core cracked in big and irregular pieces; meanwhile, the epoxy/CNT core cracked in small and regular shaped pieces. Besides, radial cracks went from a circular inner crack to an exterior circular crack. This fact clearly indicated that the composite epoxy/CNT plates had qualitatively higher energy fracture dissipation than the pure epoxy plates. This is a promissory result that needs further research.

4.2. Localized blast tests

Regarding to localized loads test, Mode I type failure was observed again with low range of explosive charges and, in these cases, the deflection was measured with a digital caliber. With higher amount of explosive charges, Mode II (tearing at the supports) and petaling was observed (Fig. 13).

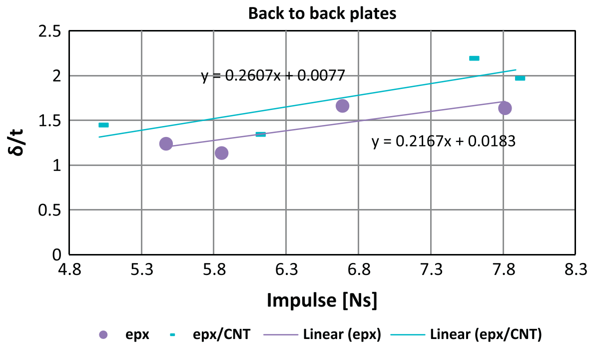

Fig. 10. Dynamic response vs. impulse. 4 mm core plates. Uniform loading.

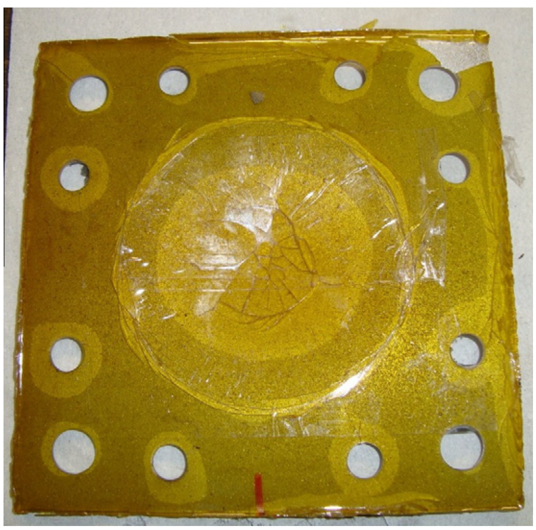

Fig. 11. Fracture pattern of epoxy core.

Fig. 12. Fracture pattern of epoxy/CNT core.

4.2.1. Sandwich plates of 2 mm core + 2Al

The results of sandwich plates of 2 mm core with two additional aluminum plates (Fig. 2) are presented in Table 4. Even when the average deflection of the epoxy/CNT plates was 10% higher than the neat epoxy plates, the difference was not significant because in this case there was a similar difference between plate thicknesses. Obviously, the additional aluminum plates had a strong influence in the plate response.

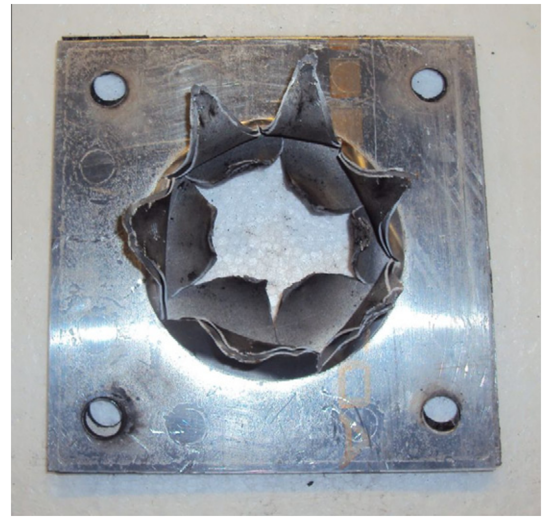

Fig. 13. Petaling failure.

4.2.2. Two sandwich plates

The results of two composites plates tested altogether (Fig. 2) are presented in Table 5. The sandwich epoxy/CNT plates presented an average deflection of 14% larger than the neat epoxy plates. Moreover, the failure load was identified. In this case, because of the higher masses of explosive, also the failure load could be determined. The failure load in epoxy/CNT plates was 18% larger than the failure load in neat epoxy plates.

5. Conclusions

A composite material composed of aluminum, CNTs and epoxy, for reinforcement of structural elements under blast loading, is presented. Experimental blast tests are carried out using uniform and localized blast loading on sandwich plates with and without CNTs.

The obtained experimental results, presented in Figs. 9 and 10 and Tables 2–5, show that the permanent displacements are larger for the plates with CNTs, as for uniform as for localized blast loading, indicating that the inherent brittleness of epoxy resins was overcome, at least partially, by adding CNTs.

On the other hand, the composite material with CNTs exhibited a fracture pattern clearly more extended than neat epoxy specimens (see Figs. 11 and 12), indicating that the composite material with CNTs exhibited better energy dissipation behavior than the neat epoxy specimens. This higher fracture energy for the case of composites sandwich plates with CNTs can be the reason for which these plates exhibit a more ductile dynamic response.

Regarding the failure load, in the case of localized blast loading, was observed that the failure load in epoxy/CNT plates was larger than in neat epoxy plates. However, it is recognized that it is necessary further research for this item, with stronger plates that allow using higher masses of explosive.

Finally, all the experimental results obtained show that, in first instance, the addition of CNTs to composite plates of aluminum and epoxy resin can result in a better performance to sustain higher explosive loading. These are promissory results to continue the research in this area.

Acknowledgements

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Special acknowledgements are extended to one of the reviewers of the first version of the paper, since his useful suggestions led to improvements of the work.

Appendix A. Measurement of impulses on ballistic pendulum

The linearised equation of motion of the ballistic pendulum, assuming viscous damping is:

$$\ddot{X} + 2\beta\dot{X} + \omega_n^2 X = 0 \tag{A.1}$$

where $\beta = \frac{C}{2M}$, $\omega_n = \frac{2\pi}{T}$ and $\omega_d = (\omega_n^2 - \beta^2)^{1/2}$ and C is the damping coefficient, M is the total mass of the pendulum including the test rig, I-beam and a balancing mass, and T is the natural period of the pendulum.

The solution of the Eq. (A.1) is given by:

$$X = \frac{e^{-\beta t}\dot{x}_0 \sin(\omega_d t)}{\omega_d} \tag{A.2}$$

where $\dot{x}_0$ is the initial velocity of the pendulum.

Let x_1 be the horizontal displacement at $t = \frac{T}{4}$ and x_2 be the horizontal displacement at $t = \frac{3T}{4}$.Substituting into Eq. (A.2) gives:

$$x_1 = \frac{\dot{x}_0 T}{2\pi} e^{-0.25\beta T} \tag{A.3}$$

$$x_2 = \frac{\dot{x}_0 T}{2\pi} e^{-0.75\beta T} \tag{A.4}$$

hence

$$\frac{x_1}{x_2} = e^{0.5\beta T} \tag{A.5}$$

giving

$$\beta = \frac{2}{T} \ln\left(\frac{x_1}{x_2}\right) \tag{A.6}$$

and

$$\dot{x}_0 = \frac{2\pi}{T} x_1 e^{0.25\beta T} \tag{A.7}$$

The impulse can therefore be calculated from:

$$I = M\dot{x}_0 \tag{A.8}$$

The natural period T is simply determined by averaging a number of measured pendulum oscillations. The damping constant, β; is calculated from Eq. (A.6) where x_1 and x_2 are found from measurements taken from several pendulum oscillations in which the pendulum was drawn back and released.

From the pendulum geometry (Fig. A1), it should be noted that the distance moved by the pendulum and that measured by the pen are not the same, and this must be accounted for.

Considering Fig. A1, the horizontal distance between the end of the pendulum and the pen when then pendulum is stationary is given by:

$$d_1 = (Z^2 - a^2)^{0.5} \tag{A.9}$$

While at its maximum amplitude, the distance decreases and is given by.

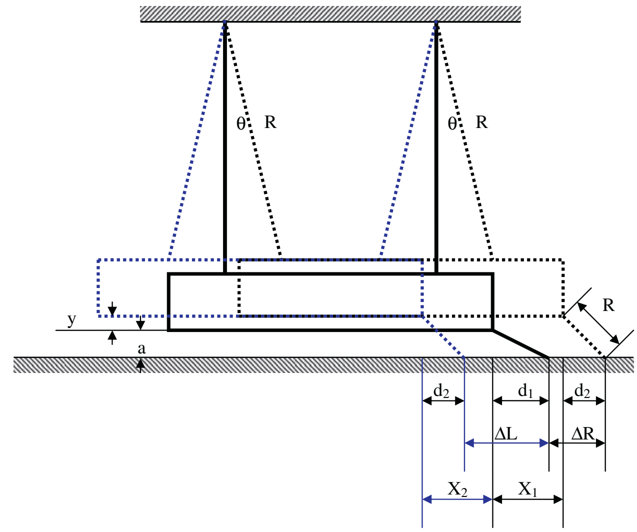

Fig. A1. Ballistic pendulum geometry.

$$d_2 = (Z^2 - (a + y)^2)^{0.5} \tag{A.10}$$

During testing, the pendulum oscillates at very low amplitudes thus giving a very small angle; θ and therefore it can be assumed that: $x_1 = R\Theta$ and $y = \frac{R\Theta^2}{2}$ Hence

$$y = \frac{x_1^2}{2R} \tag{A.11}$$

and

$$d_2 = \left(Z^2 - \left(a + \frac{x_1^2}{2R}\right)^2\right)^{0.5} \tag{A.12}$$

From Fig. A1

$$x_1 = \Delta R + d_1 - d_2$$
$$x_2 = \Delta L - d_1 + d_2$$

Substituting for d_1 and d_2, we have

$$x_1 = \Delta R + (Z^2 - a^2)^{0.5} - \left(Z^2 - \left(a + \frac{x_1^2}{2R}\right)^2\right)^{0.5} \tag{A.13}$$

$$x_2 = \Delta L - (Z^2 - a^2)^{0.5} + \left(Z^2 - \left(a + \frac{x_1^2}{2R}\right)^2\right)^{0.5} \tag{A.14}$$

where ΔL, ΔR, Z, a, and R are measured and therefore x_1 and x_2 can be calculated.

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