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Experimentation and numerical modeling on the response of woven glass/epoxy composite plate under blast impact loading

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Abstract

Background: Composite material is being used in vehicles for protective structures against blast loading. Limited data is available which compare experimental works and numerical analysis in the open field environment. More data is needed in this area in order to be able to predict and use composite materials safely.

Methods: In this work, the response of woven glass/epoxy composite plates under blast loading was investigated, both experimentally and numerically. The plate was manufactured using glass/epoxy woven Cytec 120 °C curing system. The explosive material was Tri-Nitro-Toluen (TNT) with different masses, which are 60, 80, and 100 g. The stand-off distance was also varied, ranging from 300 up to 1000 mm. In the experimental work, a sewing needle pin was put under the plate to record the maximum deformation of the plate during TNT explosion. In the numerical analysis, LS-DYNA was used extensively. The composite plate was modeled as shell elements using MAT54, and the failure criteria was Chang-Chang failure criteria. The explosive TNT material was modeled in two different ways. First, it was modeled using CONWEP and the second was modeled using Smooth Particle Hydrodynamics (SPH). The numerical analysis results were then compared with the experimental data for the case of maximum deformation.

Results: Experimentally, the sewing needle method was able to measure the plate maximum deformation during the explosion. The numerical analysis showed that the SPH model gave better agreement with experimental results compared with CONWEP method. The SPH results were in the range of 8–18% compared to experimental data, while the CONWEP results were in the range of 14–43%.

Conclusion: Albeit its simplicity, sewing needle method was able to measure the maximum deformation for blast loading experimentation. The SPH model was better compared with CONWEP method in analyzing the response of composite plate subjected to blast loading.

Keywords: Glass/epoxy composite plate, Blast loading, Smooth particle hydrodynamics, CONWEP

Background

The need for blast protection in vehicles as well as in civilian structures has increased during combat or due to terrorist attack. In the case of terrorism during the period of 1970–2016, there were 23,352 terrorist attack against civilian targets worldwide, with 78,772 deaths (Magnus, Khan, & Proud, 2018). The attacks targeted civilian vehicles such as bus, train, taxi and buildings. Therefore, there is an urgent need for blast protection structures.

Due to its lightness and high strength, composite materials are being used for ballistic and blast protection structures, such as in armored vehicle. In this case, the composite structures should be able to withstand blast loading, as required during their operational duties. Therefore, the behavior of composite structures due to blast loading should be understandable. The effect of blast loading on structures generally depended on explosive's mass and the stand-off distance between the explosive devices and the structures [Ngo, Mendis, Gupta, & Ramsay,

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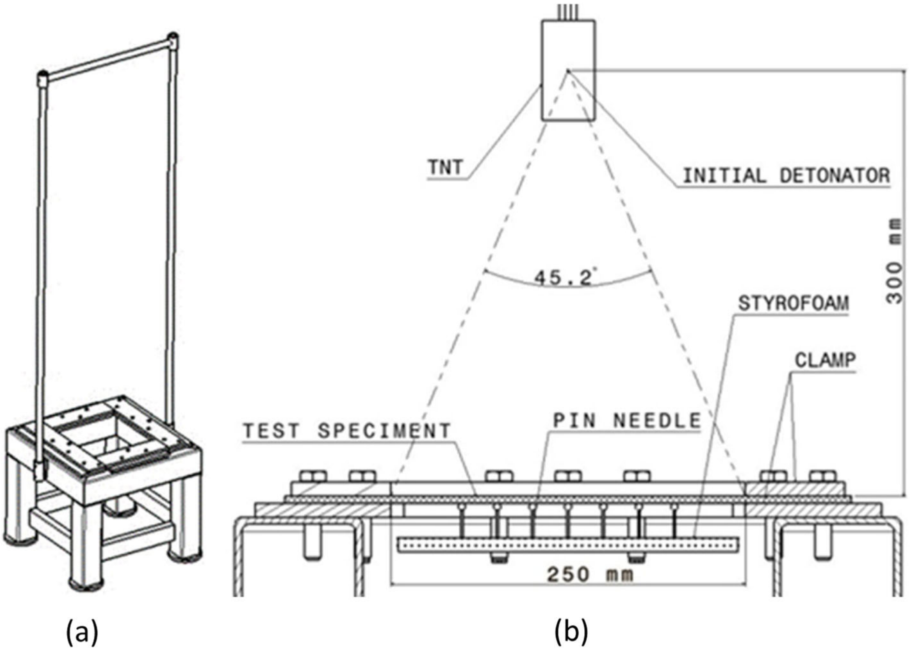


Fig. 1 Experimental set-up **a** table design and **b** experimental set-up

2007]. A 100-Kg TNT explosion at a Stand-off Distance (SoD) of 15 m will severely damage most buildings, and casualities are significantly high.

Several researches have been done in the past to study the blast loading effect on composite structures. The testing of E-glass/epoxy and S-glass/phenol plates under blast loading has been performed by Giversen, Berggreen, Benjamin, and Hayman (2014), and the deformation was measured using Digital Image Correlation (DIC) method. The numerical analysis used Load Blast Enhanced (LBE) and Fluid Structure Interaction (FSI) in LS-DYNA. The explosive mass was 25 g, and the SoD was 100 mm. The difference on the plate's displacement between the numerical model and the numerical model was around 19%. The plate was able to withstand the blast loading. In the design of marine structures, Avachat (2015) investigated composite sandwich structures to be used in the blast mitigation and the research gave criteria and data for the design of naval structures. Batra and Hassan (2008) conducted a research on the blast effect to unidirectional fiber composite structure using finite element method. From the numerical simulation analysis, they found that the fiber orientation strongly influences the energy absorption. Liang, Wang, and Wang (2007) conducted research regarding optimization of composite structure wall under blast loading. The experiment was done with variation of explosive power. Baker (1973) found out that composite blast-resistant wall tends to have a localized center failure on the surface subjected to lower level blast loading. Meanwhile, designing containment box for aircraft in-flight operation due to explosive loading using composite materials was also been done (Burns & Bayandor, 2011).

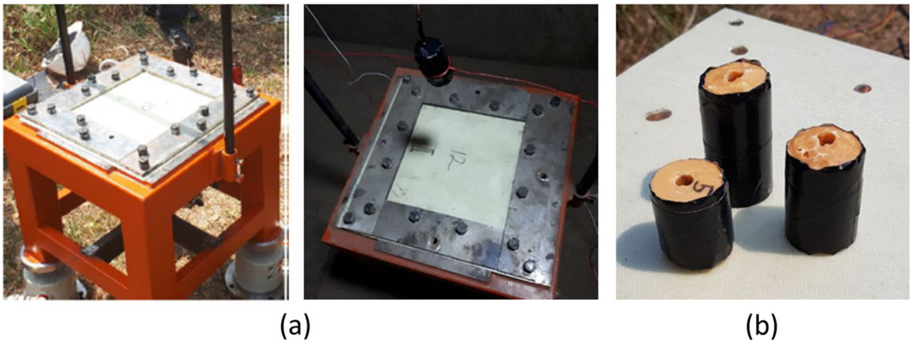


Fig. 2 **a** The actual blast table. **b** The TNT used in the experiment

Table 1 Blast experiment parameters

No.	Thickness (mm)	Material	Number of Layer	TNT (gram)	SoD (mm)
1	1.9	Fabric Glass (0/90)	10	60	1000
2	1.9	Fabric Glass (0/90)	10	60	500
3	2.3	Fabric Glass (0/90)	12	80	300
4	2.3	Fabric Glass (0/90)	12	100	300

In the numerical analysis, several methods have been used, mostly using LS-DYNA platform. Multi Material Arbitrary Language Euler (MM-ALE) and Smoothed Particle Hydrodynamic (SPH) have been used by Trajkovski (2017), while Tabatabaei and Volz (2012) compared LBE which is also called CONWEP method, MM-ALE, and the couple between LBE and MM-ALE methods. The modeling of blast in LS-DYNA is performed by Slavik (2012), while the SPH method is given by Liu and Liu (2003). The explosive material data is given in Dobratz (1981). LSTC (2017) explained the modeling of explosive material in LS-DYNA.

The above studies showed that composite materials are gaining significant importance in blast resistance structures for armored vehicle, marine structures, and aircraft structures. Therefore, studies on this field should be given more attention. Apart from Giversen et al. (2014), experimental data was lacking, especially on the plate deformation during blast loading. Deformation analysis is important since it will affect the safety of the person during blast. It should be noted that Giversen et al. (2014) used a small amount of TNT, and the experiment was conducted in a container box. Lack of experimental data on the real blast loading in open field using TNT in the amount of a standard granade. The current research aims to fill the gap.

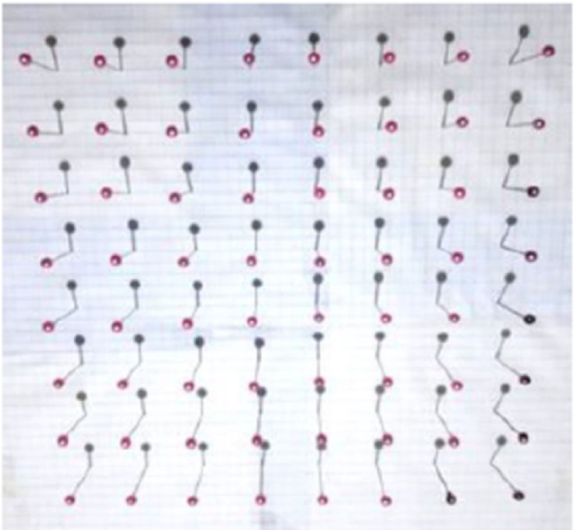


Fig. 3 Sewing pin needle system for maximum plate's deformation measurement

The scope of the current research was to conduct experimentation and numerical modeling of woven glass/epoxy response to blast loading in the open field. TNT was used with different mass, which were 60, 80, and 100 g, which is larger or equivalent to standard granede. The SoD was also varied, which were 300, 500, and 1000 mm. The limitation of the current research was that during the experimental works, only the maximum deformation of the plate was captured and measured afterwards. This is due to the nature of the experiments which were carried out in the open field not in the contained laboratory. The maximum deformation was then compared with the numerical result.

Research methodology

Experimental set-up

The composite plate was made from woven glass/epoxy materials with $(0/90)_n$ lay-ups. The plate dimension was 250 × 250 mm, and the number of layers was 10 and 12 layers. The plate was manufactured in an autoclave using Cytec 120 °C curing system. The 10 and 12 layers are chosen based on the numerical analysis of Sitompul (2018) which concluded that these layers were safe and able to withstand 100grams TNT with SoD of 1000 mm.

The design of the experimental set-up is given in Fig. 1, while Fig. 2 shows the actual table and the TNT used during the blast experimentation. Note that in Fig. 1 it shows the set-up for SoD of 300 mm, while in the

Table 2 Material properties of woven glass/epoxy

Property	Symbol	Value	Unit
Density	RO	1900	kg/m^3
Young's modulus longitudinal direction	E11	13259	MPa
Young's modulus transverse direction	E22	13259	MPa
Shear modulus	G12	3032	MPa
Longitudinal compressive strength	XC	307	MPa
Longitudinal tensile strength	XT	261	MPa
Transverse compressive strength	YC	307	MPa
Transverse tensile strength	YT	261	MPa
Shear strength	SC	80	MPa
Poison ratio	PRBA	0.159	–

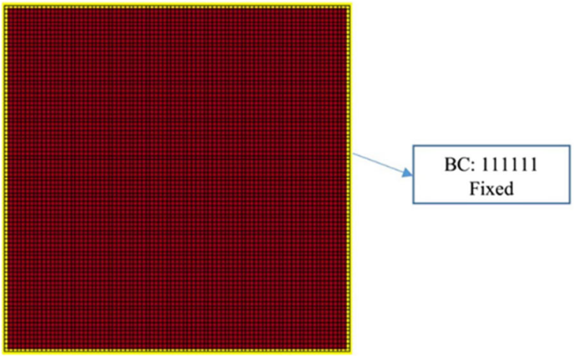


Fig. 4 Modeling glass/epoxy plate shell elements. Element size was 3 × 3 mm

experimentation the SoD was varied from 300, 500, and 1000 mm. The other dimension was the same. Two load cells were installed in the two of the table legs. The load cells were used to record the load history during the blast.

As in Fig. 2, the plate was bolted into the table to act as a rigid body boundary condition. Since there are bolt connection, the working area of the composite plate was reduced to 250 × 250 mm. The high-explosive TNT was hanged at support rod at the centre of the specimen. The TNT was in the form of cylinder with the diameter of 37 mm, and the height was 38, 50, and 63 mm to give the TNT mass of 60, 80, and 100 g, respectively.

The experimental configuration is given in Table 1. Due to limited number of TNT available, since it is a military explosive, only four experimental configurations were tested, with variation of number of layers 10 and 12, the explosive mass, which are 60, 80, and 100 g and the stand-off distance (SoD) of 300, 500, and 1000 mm as shown in Table 1. The different variations aimed at getting as much as possible the experimental data that can be compared with the numerical analysis.

In the experimental work, the focus was on the measurement of the maximum deformation at the centre of the plate during explosion. The maximum deformation was recorded using a simple method called sewing needle pad method as is shown in Fig. 3. The sewing needle pad was placed under the specimen. The pad was made of Styrofoam, and the sewing needle was stuck in the foam. When the specimen deformed due to blast loading, the deformation will be recorded by the displacement of the needle when it sank to the Styrofoam.

Table 3 Material properties and JWL equation of state parameter for TNT

ρ(kg/m3)	D(m/s)	P_{CJ}(GPa)	A (GPa)	B (GPa)	R_1	R_2	ω	E(J/m^3)
1540	6930	21	3.712	3.231	4.15	0.95	0.3	7E+09

Numerical analysis

In the numerical analysis using LS-DYNA software, the glass/epoxy plate was modeled using shell elements in the type of MAT54 or MAT Enhanced_Composite_ Damage. The material property of the glass/epoxy is given in Table 2.

The boundary conditions were clamped at all edges. The optimum element size was determined during the convergence test. It was found that the ideal mesh size was 3 × 3 mm. Figure 4 shows the plate mesh element and the boundary conditions. Both LBE and SPH methods used the same shell elements model for the glass/epoxy plate. The element formulation used fully integrated shell element, ELFORM = 16.

Load blast enhanced model

LBE is an empirical pressure load calculation which is provided based on experimental database which has roots similar to CONWEP. Blast loading model using LBE is quite simple. The only one that needs to be discretized is the plate structure. In LS-DYNA, *LOAD_BLAST_ENHANCED card is used to define the blast loading. The input data are the equivalent mass of TNT and explosive charge coordinate. The UNIT has to be selected correctly, and the blast type chosen is spherical-free air burst as default, BLAST = 2. Empirical air blast model is calculated by Friedlander equation (Baker, 1973):

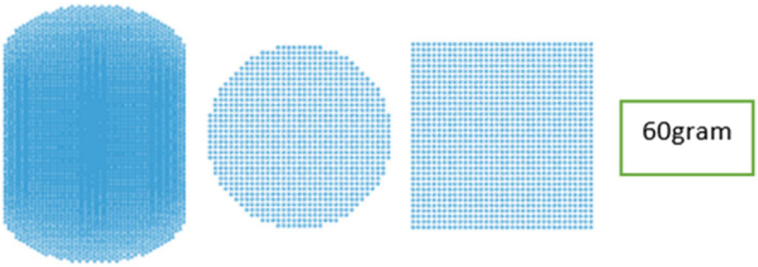


Fig. 5 Discretization of explosive TNT by SPH method

$$P(t) = P_{SO}\left(1-\frac{t}{t_0}\right)e^{-b\frac{t}{t_0}} \tag{1}$$

When a shock wave hit the surface of the plate, it may face an oblique angle of incidence. Then, the effective pressure of this model described the blast load equation is (Slavik, 2012):

$$P(\tau) = P_r\ cos^2\theta + P_s\left(1 +\ cos^2\theta - 2cos\theta\right) \tag{2}$$

where θ is the angle of incidence. P_r is the peak reflected pressure, and P_s is the peak of incident pressure. In *LOAD_BLAST_ENHANCED keyword model, the inputs are the equivalent mass of TNT, the coordinate location of explosion, and the time-zero of explosion that describes when the blast will start. The load blast need to be applied on all composite elements as a segment; hence, *LOAD_BLAST_SEGMEN_SET card has to be defined. This card registers the set of shell element and recall *LOAD_BLAST_ENHANCED card.

Smooth particle hydrodynamics model

Smoothed particle hydrodynamic (SPH) method is a mesh-free method which is discretised by unconnected particles for describing physical governing equation. The body that uses SPH state system is represented by a set of particles that have individual physical properties and freely move according to governing conservation equation (Liu and Liu & Liu, 2003). The SPH of explosive model is generated by using SPH generation with cylinder method in LS-DYNA software. For example, SPH model of the TNT explosive is shown in Fig. 5 for the case of 60-g TNT. During the convergence test, it was found that it needed 65,727 nodes to model the explosive TNT.

Table 4 Material property and linear polynomial equation of state for air

ρ (kg/m^3)	γ	C_0	C_1–C_3, C_6	C_4, C_5	E_0 (J)	V_0
1.29	1.4	-1×10^{-6}	0	0.4	2.5×10^5	1

Explosive material TNT is modeled by using *MAT_HIGH_EXPLOSIVE_BURN card and its properties is in Table 3. The equation of state (EOS) that represents the pressure as function of density and internal energy has to be defined in numerical model. *EOS_JWL card is used on this purpose. The pressure equation of state is given by Dobratz (1981):

$$p = A\left(1-\frac{\omega\eta}{R_1}\right)e^{-\frac{R_1}{\eta}} + B\left(1-\frac{\omega\eta}{R_2}\right)e^{-\frac{R_2}{\eta}} + \omega\eta\rho_0 e \tag{3}$$

where η is the ratio of density of explosive gas to initial density of explosive material, *e* is internal energy per unit mass, *A*, *B*, R_1, R_2, and ω are the coefficients that extracted from fitting curve of experimental data. The input parameter of Jones-Wilkins-Lee (JWL) is given in Table 3 (Trajkovski, 2017).

This research compared the blast loading simulation with and without the SPH of air model. The air of environment condition is assumed to be an ideal gas.

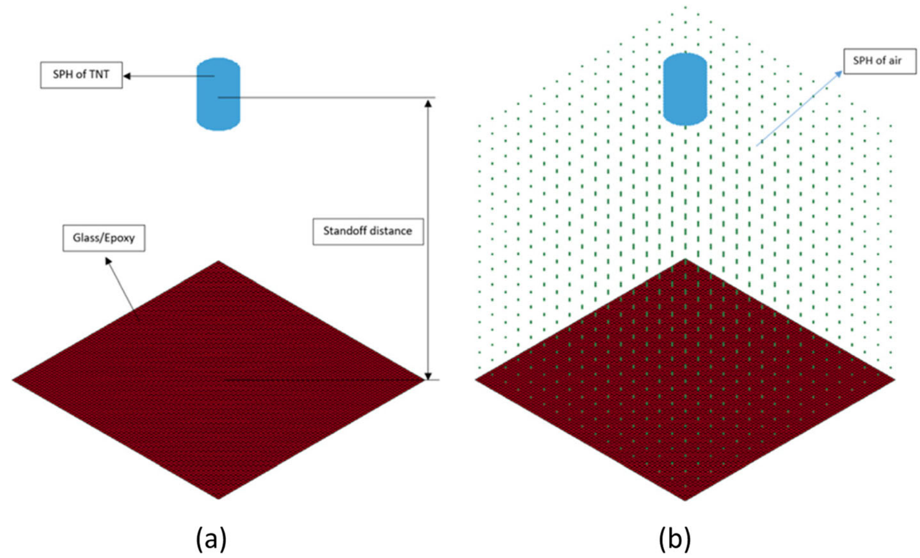
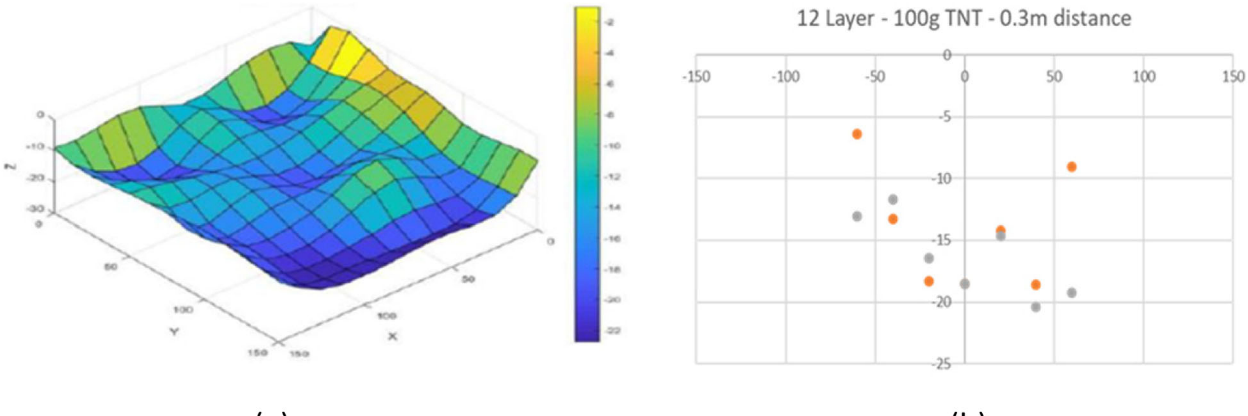


Fig. 6 Glass/epoxy and SPH explosive model: **a** without air model and **b** with air model



(a) (b)

Fig. 7 Deformation of specimen code S4 **a** contour and **b** displacement point measured by the sewing needle

Therefore, pressure equation of state for perfect gas is given in Eq. 4 [LSTC, 2017]:

$$p = \frac{(\gamma - 1)\rho}{\rho_0} E \tag{4}$$

where E is the specific internal energy, ρ is the current density, ρ_0 is the initial density of air, and γ is the ratio of the specific heat. The material model for air used *MAT_NULL card, and the equation of state definition used *EOS_LINEAR_POLINOMIAL card. The material property and equation of state of air were given in Table 4 (Trajkovski, 2017).

The contact definition used *AUTOMATIC_NODES_TO_SURFACE_SMOOTH to define particles of SPH and the shell surface. The particles approximation between two different SPH parts is computed (CONT = 0) and the space dimension of SPH particles is 3D problems (IDIM = 3). The final model of glass/epoxy under blast loading with and without SPH model is given in Fig. 6.

The parametric studies in numerical model must be conducted to get the robust model. The shell mesh size and the number of particles of SPH were varied to gain convergence value. The time step coefficients (TSSFAC) and smoothing length coefficient (CSHL) were investigated in those various values.

Table 5 Maximum deflection during explosion for different configuration

Specimen code	Number of plies	Mass of TNT (grams)	Stand-off-distance (mm)	Experimental maximum deformation (mm)
S1	10	60	1000	11.1
S2	10	60	500	13.8
S3	12	80	300	20.3
S4	12	100	300	22.3

Results and discussion

Experimental results

In all the tests, the specimens did not fail or rupture after the blast loading. Thus, the specimens were able to withstand the blast loading. The displacement of each point measured in each sewing pin were collected and represented as a contour. Figure 7a is an example of displacement contour for specimen having 12 layers and 100-gram TNT with 300 mm stand-off distance, while Fig. 7b gives the displacement point of the needle along the plate's central line. From Fig. 7b, the experimental maximum deformation of the plate during the TNT explosion can be determined.

The summary of the experimental maximum deformation measured by the sewing pin needle is given in Table 5.

Table 5 shows that experimentally, the plate maximum deformation during the blast loading depended on the plate thickness, the mass of TNT, and the SoD. The larger TNT mass and the shorter SoD will produce higher deformation. It shows that shortening the SoD by half and keeping the same number of layers and the mass of TNT will produce an increase of the deformation by

Table 6 Comparison of plate's maximum deformation result between experimental data and SPH simulation without air model

			Maximum deformation		
Number of plies	TNT (gram)	SoD (mm)	Experiment (mm)	Numerical (SPH simulation without air model)	Difference (%)
10	60	500	13.8	3.75	73
12	80	300	20.3	8.17	60
12	100	300	22.2	8.95	60

Table 7 Comparison of plate's maximum deformation results between experimental data and SPH simulation with air model

Number of plies	TNT (gram)	SoD (mm)	Maximum deformation		Difference (%)
			Experiment (mm)	Numerical (SPH simulation with air model), mm	
10	60	1000	11.1	9.11	18
10	60	500	13.8	12.68	8
12	80	300	20.3	18.19	10
12	100	300	22.2	19.18	14

24%. Therefore, SoD gives significant factor on the maximum deformation.

Numerical analysis results

SPH methods

The glass/epoxy composite structure under blast loading has been simulated numerically with SPH method. The first model is without modeling the air. The numerical results are compared with the experimental data for different test conditions. Table 6 shows this comparison. It shows that the SPH numerical model without modeling the air predict the maximum plate deflection much lower compared with maximum deflection measured during experimentation. The difference was as high as 70%.

Table 6 shows that the SPH method excluding air modeling are inaccurate for all the specimen configuration. It seems that without air model, the pressure from the TNT explosion was not transferred perfectly to the plate, resulting in the much lower maximum deformation of the plate.

The second model is the inclusion of air model into the SPH method, as in Fig. 5b. The result is given in Table 7. It shows that the resulted maximum deformations are closer to the experimental ones. The error is between 8 and 18% compared to the experimental data. Therefore, the inclusion of air model into the SPH method is necessary to get better results.

Comparison between LBE and SPH methods

Figure 8 compares experimental data with both LBE and SPH method for the maximum deformation of woven glass/epoxy plate during the explosion. It shows that the SPH method predicts maximum deformation better than the LBE method when these compared with experimental

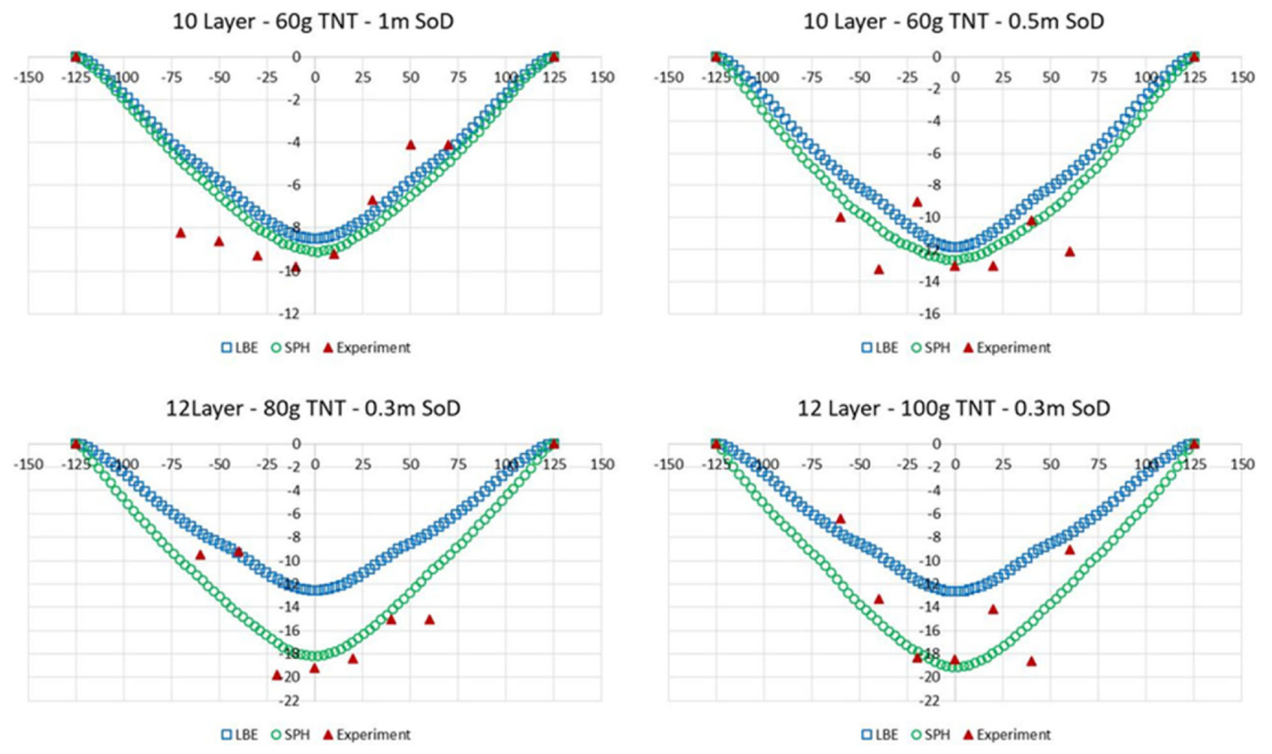


Fig. 8 Experimental vs numerical deflection results using LBE and SPH methods

Table 8 Comparison of maximum deformation of central line of specimen experiment and LBE simulation result

			Maximum deformation				
Number of Layer	TNT (gram)	SoD (mm)	Experiment (mm)	LBE method (mm)	Diff. (%)	SPH method (mm)	Diff. (%)
10	60	1000	11.1	8.47	27	9.11	18
10	60	500	13.8	11.83	14	12.68	8
12	80	300	20.3	12.54	38	18.19	10
12	100	300	22.3	12.66	43	19.18	14

data. Overall, LBE method gives lower maximum deformation compared with SPH method and experimental data. Note that SPH method included air model in the calculation.

The summary of glass/epoxy plate's maximum deformation is given in Table 8. As shown in Table 8, the SPH method is more accurate than the LBE method. The maximum deformation of SPH method is closer with the experiment data with error less than 18%.

Table 8 shows that numerical analysis gives smaller deformation compared with the experimental results. Numerical analysis produces higher stiffness compared to the real structures. LBE method produces even smaller deformation compared to SPH method. LBE method does not consider the air which transmit blast loading from the TNT to the plate. It should be noted that without modeling the air even in SPH method will also produce smaller deformation, as is given in Tables 6 and 7. Therefore, including the air model is important in producing maximum deformation which is comparable with the experimental data.

Table 8 shows that the SoD was the dominant factor in the blast loading. The same number of layers, 12 layers, with the same SoD, 300 mm, and increasing the amunt of TNT by 25% (80 to 100 g) will increase the maximum deformation by 10% (20.3 to 22.3 mm). On the other hand, keeping the same number of layers (10 layers) and TNT (60grams), while shortening the SoD 50% (1000 mm to 500 mm), produced the increase of deformation of the plate by 24%. Further studies should be carried out to investigate this finding, both experimentally and numerically.

Conclusion

Experimentation and numerical modeling on the response of woven glass/epoxy composite plate under TNT blast loading has been conducted. The lay-up was [0/90]n and the number of layers were 10 and 12 layers. The dimension of the plate was 250 × 250 mm. The mass of TNT were varied which were 60, 80, and 100 g, while the stand-off distance was 300, 500, and 1000 mm. No rupture was found in all specimens. The woven glass/epoxy was able to sustain the blast loading. The maximum deflection at the centre of the specimens was recorded using sewing needle pin technique.

The numerical analysis used LBE and SPH methods. It was found that SPH method give better prediction compared to the experimental data compared to the LBE method. The maximum difference was 18%, less than the results of Giversen et al. (2014). The error of using LBE method varied from 14 to 38% compared with the experimental data, while the error in using SPH method was less than 10%. In modeling the blast using SPH method, it was necessary to include air model in the analysis. Excluding air model grossly underestimated the maximum deflection of the plate.

Further experimentations shoud be carried out to complete the present findings.

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Authors' contributions

GK and HH did experimentation; MRS and AK conducted numerical analysis. GK was the coordinator for the work and reported to BKH. BKH is GK's PhD supervisor, who guided and supported his work. BKH is also MSc supervisor for HH, MRS, and AK. BKH wrote the major part of the paper. All authors read and approved the final manuscript.

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Availability of data and materials

The raw data is available at https://sites.google.com/view/glass-fiber-blast-test/beranda

Competing interests

The authors declare that they have no competing interest.

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