Gazi University Journal of Science
GU J Sci
26(2): 253-259 (2013)

Inspection of Failure Caused by Ballistic Impact on Body Armors Composed of Laminated Dyneema™

Veysel ALANKAYA[1,♠], H. Kemal ŞENYILMAZ[2], Mehmet TÜRKER[3]

[1]*Department of Naval Architecture & Marine Engineering, Yıldız Technical University, Istanbul*
[2]*Department of Mechanical Engineering, Gazi University, Ankara*
[3]*Department of Mechanical Engineering, Kocaeli University, Kocaeli*

Received:14.10.2011 Accepted:20.12.2012

ABSTRACT

In order to establish the survivability of law enforcement officers who may face a variety of risks in their work, it is important to predict the damage of armor caused by small caliber guns, which are widely used by street gangs all over the world. Due to the weight considerations, use of light weighted composites for body armor has continued to increase over years. Nevertheless, determining the damage capability of composite laminates against ballistic impact is not a simple problem as determining elastic stiffness of the armor due to the complex damage modes, which can occur in composites through impact phenomenon. This study presents the effects of impactor velocity to penetration mechanism. Additionally, the ballistic damage of Dyneema™ plates at different velocities are presented supported by real test reports.

Keywords: Body armor, Laminated composite, Ballistic damage, Dyneema™

1. INTRODUCTION

Today, wars seem to be fought by smart bombs and technological equipments; however certain victory requires combating at close quarters, as can be seen by the situation in Iraq or Afghanistan. It is not necessary to go away from homeland to be a part of battle. Nowadays, streets are becoming battle scenes of local gangs using handguns to cause fatal risks for domestic security forces and civilian.

The protection of soldiers and security forces against small caliber guns, which are the instruments of close quarter, requires developing body armors depending on the threat level concepts. Although the material of armor has to be compatible with the threat level, as it has no meaning over determined calibers. Additionally, the physical abilities of the personnel have to be considered. For an instance; the fighting load of a soldier affects the walking speed so the transfer rate of the troop, or body armor with shoulder and neck protection parts may prevent police officer to move quickly.

Conversely, Wambua [1] defines that; due to the weight considerations, use of ceramics for body armor has continued to increase over years. Ceramics are, however, brittle and normally have to be backed by a laminate of high strength and high modulus.

Modern composites have created a revolution in lightweight body armors. Their advantages relative to conventional materials such as high strength to weight and stiffness to weight ratios, superior resistance to environmental conditions, design flexibility also known as tailoring the material for desired application, make

♠Corresponding author, e-mail: valankaya@hotmail.com

them attractive for a wide range of applications at different threat levels and environment [2,3].

Laminated composite plates are made up of two or more layers of materials bonded together to form a new material. The properties of the laminate can be tailored for a desired application. However, the analysis of composite laminates brings additional difficulties to the analyst such as the inter-laminar or transverse shear stress due to mismatch of material properties among layers, bending-stretching coupling due to asymmetry of lamination, and in-plane orthotropy. Extra complexities arise by the necessity of the satisfaction of the prescribed boundary conditions. Therefore all these advancements and design requirements place a premium on an in-depth understanding of the response characteristics of such structural components.

The structural analysis of laminated composite plates is performed generally by approximate numerical methods, such as finite element methods (FEM), boundary element methods (BEM), and more recently developed meshless Petrov-Galerkin methods. Derivation of analytical (e.g., Fourier series) solutions for the problems of laminated plates fabricated with such advanced composite materials as graphite/epoxy, Kevlar/epoxy, boron/epoxy, graphite/PEEK, etc., is, however, fraught with many complexities as briefly mentioned above. Notwithstanding; Karakuzu et al [4] defines that, the numerical evaluation of impact with a linear static finite element analysis is not very accurate, but it gives a meaningful insight on the major mechanisms of failure. However, it is required by contractors that the armor shall be proven by real shots to define impact damage.

Additional complexities occur while composite material resists to the impact loads. Impact loads are classified into three categories by Naik and Shrirao [5]; low velocity impact, high velocity impact and hyper velocity impact, because of the differences on energy transfer between projectile and target, energy dissipation and damage propagation mechanisms undergo drastic changes as the velocity of the projectile changes. In low velocity impact regime; the support conditions are crucial as the stress waves generated outward from the impact point have time to reach the edges of the structural element, causing its full-vibrational response. In high velocity impact, which is known as ballistic impact; the response of the structural element is governed by the local behavior of the material in the neighborhood of the impacted zone, the impact response of the element being generally independent of its support conditions. Hyper velocity impact involves projectiles moving at extremely high velocities such that the local target materials behave like fluids and the stress induced by the impact is many times the material strength.

2. FAILURE MODES

When a impactor impacts to a composite armor plate; instantaneous stresses produced and immediately transmit to remaining parts of the plate. However, the stress distribution depends on the material properties and the thickness or structural design of the armor. Naik and Doshi [6] presented that; if the deformation behavior along the thickness direction of the target is same along the entire thickness, the wave propagation through the thickness direction is not considered therefore it shall be accepted as thin target. Conversely, wave propagation along the thickness direction shall be considered for thick targets, therefore deformation and the induced stress behavior of the target would be different at various locations along the thickness direction.

Sutherland and Soares [7] defined the damage mechanism of composite plates and reported that the most important variations seen were between the responses of thin and thick composites. Thin plates suffered internal de-lamination but this was not seen to affect the response significantly. High deflections gave a membrane stiffening effect until at high incident energies back-face fiber failure led to perforation. Thick plates showed both significant shear and indentation deformation. A bi-linear force-displacement response as de-lamination led to a significant stiffness reduction was seen, followed by front-face initiated fiber failure leading to perforation and/or shear failure.

For the analysis of thick targets, the wave propagation along the thickness direction shall be considered. The wave propagation through the thickness direction causes different failure reactions inside the target depending on the contact force, mass and velocity of the impactor, which designates the impact kinetic energy. The dominant damage mechanisms of composite laminates are determined as de-lamination and fiber failure by Johnson et al [8]. Tita et al. [9] defines these failure mechanisms by two modes. Intra-ply failure which damages at fibers, polymeric matrix and/or interface between fibers and matrix. Secondly, inter-ply failure mode that consists of delaminations between plies.

These failures, both intra-ply and inter-ply; absorb a fraction of impact energy. If an object with mass m impacts a composite plate with a velocity vo, the impact energy of the impactor E_i can be expressed as follows;

$$E_i = \frac{mv_0^2}{2} \tag{1}$$

The kinetic energy *KE(t)* transferred from object to the composite laminated plate can be expressed;

$$KE_{(t)} = \frac{mv_0^2}{2} - \frac{m(v_i(t))^2}{2} = E_e + E_a \tag{2}$$

where the velocity of the impactor $v_i(t)$ can be obtained by [9];

$$v_i(t) = v_0 - \frac{1}{m}\int_0^t F_{\exp} dt \tag{3}$$

The experimental impact force F_{exp} shall be measured during the impact tests. Thus, it is possible to evaluate the impact energy, which reaches the composite plate, as well as the absorbed energy (Ea) and the elastic energy (E_e). Tita et al. [9] defines the absorbed energy as "released energy", because the failure mechanisms activated during the impact event release energy, which is absorbed by the structure and is not transformed on elastic vibrations. Sutherland and Soares [7] noted the importance of difference between impact resistance, which means the resistance of the material to impact damage and impact tolerance, which defines the performance of the material once a given impact has occurred.

Furthermore, the amount and the type of failure mechanisms activated depend on some factors: Mass, velocity and geometry of the impactor, geometry of the structure, type of fiber and/or matrix used for manufacturing of the composite plate, stacking sequence of the plies. Final damage is sensitive to even small changes in the fiber/resin type, ratio, architecture, interface and laminate production method. Therefore it is important to realize that a laminate that performs well in one area may not perform well in another. So, further information shall be considered during and after experiments as to how well plate resists de-lamination, fiber damage, perforation, plunging, bushing, crater shape and how the stiffness is affected by damage.

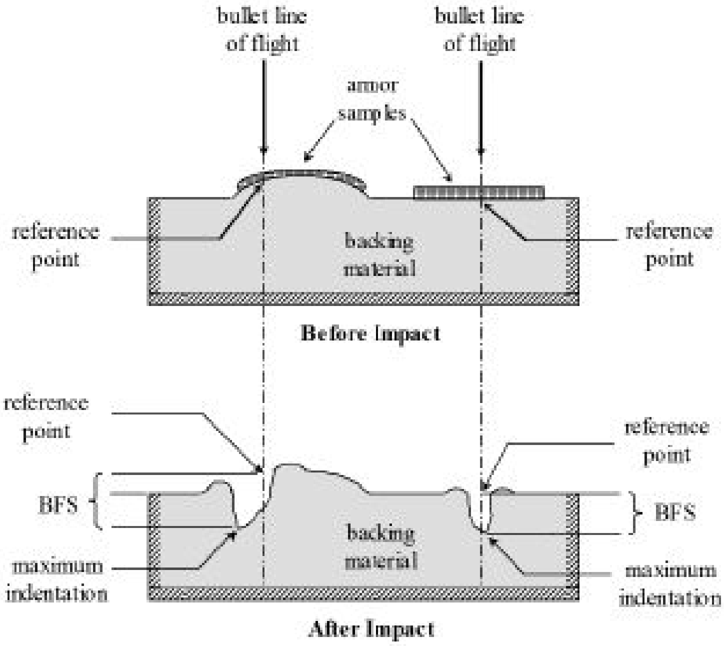

Figure 1. Examples of BFS Measurement [10].

While the subject is the lives of human beings, the armor shall be tested absolutely defining if the back side of it is safe or not. Therefore ballistic tests perform the back face trauma which examines the depth of perforation. It defines the real effect or bullet or impactor behind the protection which causes the injury in brief. Back Face Signature (BFS) criteria have been performed by National Institute of Justice (NIJ) and define trauma limits as can be seen at Ref. [10]. The measurement of BFS is shown at Figure 1 which BFS depth differs according to armor shapes.

In this study, experimental results of armor inserts made by Dyneema™ are presented to show damage mechanisms and trauma levels.

3. EXPERIMENTAL RESULTS

Tests were performed at TNO facilities on Rijswijks/Holland under defined specifications at Table1. An overview of small calibre indoor firing facility is shown at Fig 2.

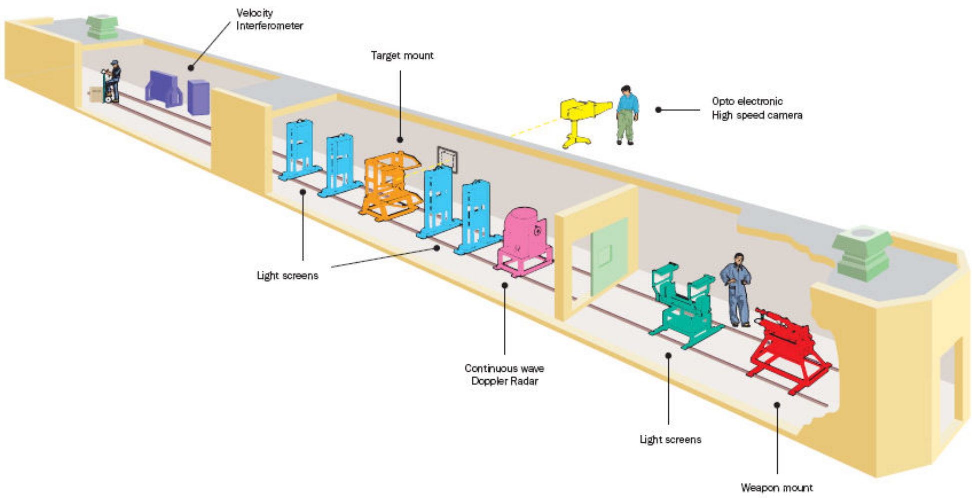

Figure 2. Overview of Small Calibre Indoor Firing Range at TNO [11].

Table 1: Ballistic specifications of performed test.

		Ballistic Specifications
Weapon		SVB
	Barrel Length	665 mm
	Rifling Twist	1:254
Projectile		7,62x51 Ball (Sintox)
	Weight	9,55 gram
	Calibre	7,62 mm
	Manufacturer	Metallwerk Elisenhuttle Gmbh.
Distance muzzle to target		7,8 m
Target obliquity		0^{o} NATO

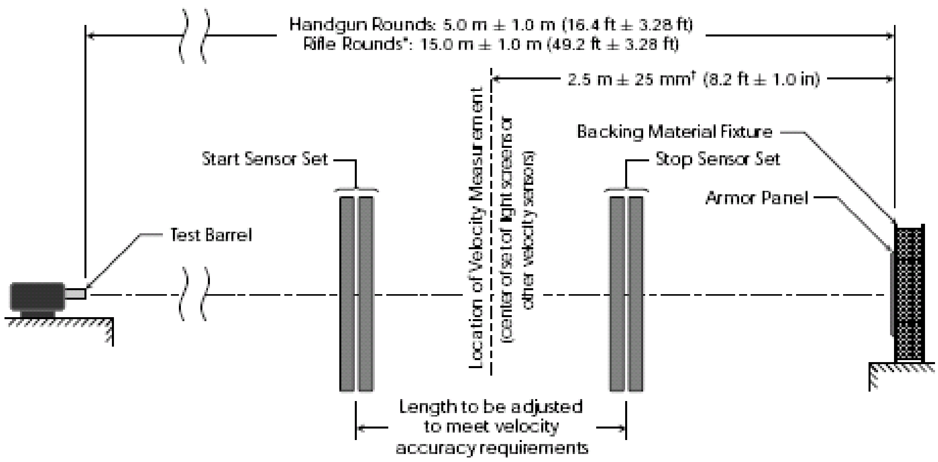

Figure 3. Test Setup [10].

Test setup as shown at Fig 3 and Fig 4 is explained as "For rifle rounds the length may be further adjusted to minimize yaw at impact; however, in such cases the yaw at the impact must be experimentally shown to be less than 5^{o} and reasonably close to minimal tolerance for 0^{o} shots. [10]"

Two inserts were tested against the same threat level which is defined at Ref. [10] as NIJ III which is explained as; "Type III plate inserts shall be tested in conditioned state with 7.62 mm Full Metal Jacket (FMJ), steel jacketed bullets with a specified mass of 9.6 g and a velocity of 847 m/sn ± 9.1 m/sn".

The test equipment shall be arranged as shown in Fig 4. For handgun rounds, the armor panel shall be mounted 5.0 m. ± 1.0 m. from the muzzle of the test barrel and for rifle rounds, the armor panel shall be mounted 15 m.

± 1.0 m. from the muzzle of the test barrel. In order to minimize the possibility of excessive yaw at impact, or for other range configuration reasons, the distance may be adjusted for each threat; however the distance shall not be less than 4 m. for any round. In the case of rifle rounds, if the distance is adjusted to less than 14 m. the bullet yaw shall be experimentally verified to confirm that the angle of incidence is within 5^o of the intended angle [10].

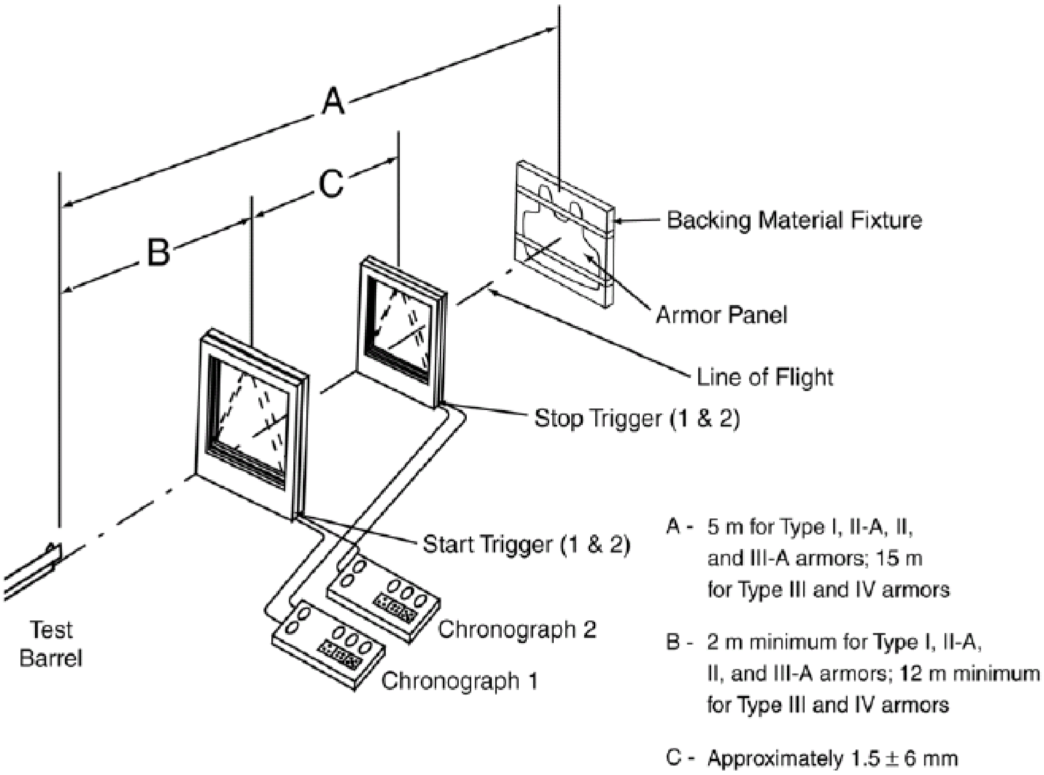

Figure 4. Test Range Configuration [10].

The backing material fixture should be rigidly held by a suitable test stand, which shall permit the entire armor and backing material assembly to be shifted vertically and horizontally such that the entire face of the backing material can be targeted [10].

BFS's are measured by impact tests to demonstrate the armor's pass/fail penetration capability. Test series require the use of a plastically deforming witness media (clay backing material) held in direct contact with the back surface of the armor panel. This configuration is used to capture and measure the BFS depression produced in the backing material during nonperforating threat round impacts. The use of clay backing material and the subsequent BFS depth measurement does not reflect, represent, replicate or duplicate the physical characteristics of the human torso or its physical response to this type of stimulus [10].

Comparison of inserts is presented at Table 2 and it can be seen that both insert #1 and #2 are identical. Test results are presented in order of sample numbers by means of shot numbers. Additionally, shot numbers can be examined by the way of test shot order for dedicated insert. Figure 5 represents the impact locations which have the same numbers with shots on the inserts. The importance of shot locations is the indication of insert resistance against impact energy.

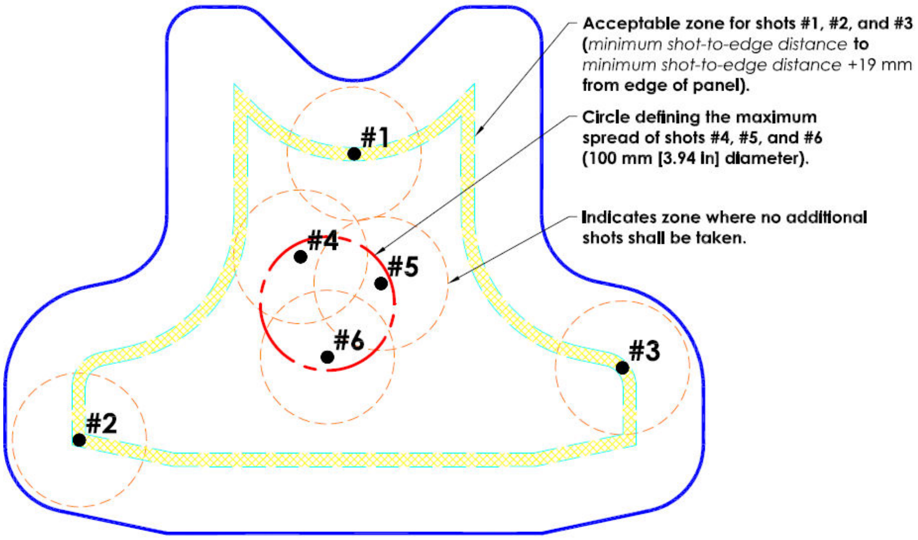

Figure 5. General armor panel impact locations (front and back) [10].

It is a must to explain complete and partial penetration before examination of test results as follows,

- Complete Penetration (CP) : The complete perforation of an armor sample or panel by a test bullet or by a fragment of the bullet or armor sample itself, as evidenced by the presence of that bullet or fragment (armor or bullet) in the backing material or by a hole which passes through the armor and/or backing material.
- Partial Penetration (PP) : Any impact that is not a complete penetration is considered a partial penetration.

Table 2: Comparison of inserts.

	Insert No.1	Insert No.2
Size	300 x 250 mm^2	300 x 250 mm^2
Thickness	16 mm	16 mm
Weight	1102 gram	1085 gram
Areal Mass	14.7 kg/m^2	14.5 kg/m^2
Composition of sample	Insert 66 ply + Stimpex 35 ply Kevlar 802	Insert 66 ply + Stimpex 35 ply Kevlar 802

Table 3: Test results of insert #1 according to impact (shot) numbers.

Shot No.	Impact Velocity (m/sn)	Indent Depth (mm)	Stop/Perforation
1	838	42	Stopped
2	849	39	Stopped
3	849	43	Stopped
4	846	48	Stopped
5	839	44	Stopped
6	845	48	Stopped

Table 4: Test results of insert #2 according to impact (shot) numbers.

Shot No.	Impact Velocity (m/sn)	Indent Depth (mm)	Stop/Perforation
1	855	41	Stopped
2	845	43	Stopped
3	852	47	Stopped
4	850	47	Stopped
5	855	44	Stopped
6	849	53	Stopped

Each insert has been tested by six fair hit impacts and recorded BFS values of first shot and the highest remaining velocity shot on each armor insert.

4. CONCLUSION

Before inspection of test values, acceptance criteria for penetration and BFS compliance must be indicated as follows;

- No perforation through the panel, either by the bullet or by any fragment of the bullet or armor.
- No measured BFS depression depth greater than 44 mm. for the first shot and the highest remaining velocity shot for each armor insert.

Therefore, both inserts are qualified as NIJ III level protection however the behavior against impact energy changes as well as BFS indentations.

First shots have 838 m/sn and 855 m/sn impact velocities for inserts #1 and #2 respectively. It is spectacular that indent depths are relatively similar as 42 mm. and 41 mm. even impactor energy increases square of velocity as described at Equation 1.

Highest remaining velocity shots have 849 m/sn and 855 m/sn impact velocities for inserts #1 and #2 respectively. It is also noteworthy that indent depths are relatively similar as 43 mm. and 44 mm. in contravention of increasing impact velocity.

It should be noted that; behavior of composites may change according to production methodology even some procurement differences may cause weakness as can be seen from experimental results. Insert #1 shows maximum indentation 48 mm. for 845 m/sn impact velocity at shot number 6, however, second insert handled the same impact by 43 mm. indentation.

The difference between the inserts is just a little change in procurement process. The inserts of body armors have inclination to be suitable for human body. The process needs to have inclined moulds to press polyethylene plies under uniformly distributed load to prevent compact and uniform curing. First insert was produced by a mould with the same radius of the body armor. But the second one has been produced by another mould which had greater radius than the body armor.

The effect of the mould can be assessed as the uniform pressure press distribution and the equivalent thermal interaction between the plies. These test results show that the second insert has a compact body and uniform combination because of the mould effect. High density polyethylene (Dyneema™) plies has been formed for their higher capability by procurement process correction.
Additionally, shot locations cause different results as the same insert may have different indentations at same impact velocities. From this point of view, it is a must to examine indentations for the same shot locations. However it can be seen that the second insert has relatively less BFS indentation values than the first one as well as the shot (impact) numbers.

REFERENCES

[1] Wambua, P., Vangrimde, B., Lomov, S. and Verpoest, I., "The response of natural fiber composites to ballistic impact by fragment simulating projectiles", ***Composite Structures*** 77:232-240 (2007).

[2] Swanson S.R., Introduction to Design and Analysis with Advanced Composite Materials, ***Prentice Hall Inc***. (1997).

[3] Jones R.M., Mechanics of Composite Materials, ***Taylor & Francis, Inc***., Second Edition (1999).

[4] Karakuzu, R., Erbil, E. and Aktas, M., "Impact characterization of glass/epoxy composite plates: An experimental and numerical study", ***Composites : Part B*** 41:388-395 (2010).

[5] Naik N.K. and Shrirao P., "Composite structures under ballistic impact", ***Composite Structures*** 66:579-590 (2004).

[6] Naik N.K. and Doshi A.V., "Ballistic impact behaviour of thick composites: Parametric studies",***Composite Structures*** 82:447-464 (2008).

[7] Sutherland, L.S. and Soares, C.G., , "Impact behaviour of typical marine composite laminates", ***Composites : Part B,*** 37:89-100 (2006).

[8] Johnson, H.E., Louca, L.A., Mouring, S. and Fallah, A.S., , "Modelling impact damage in marine composite panels", ***International Journal of Impact Engineering*** 36:25-39 (2009).

[9] Tita, V., Carvalho J. and Vandepitte D, , "Failure analysis of low velocity impact on thin composite laminates: Experimental and numerical approaches", ***Composite Structures*** 83:413-428 (2008).

[10] Mukasey, M.B., Sedgwick, J.L. and Hagy, D.W., , "Ballistic Resistance of Body Armor, NIJ Standard-0101.06", ***US Department of Justice*** (www.ojp.usdoj.gov/nij). (2008)

[11] http://www.tno.nl/downloads/defind_land_testfaciliteit, (2012).