Performance of Composite Structures Subjected to High Velocity Impact -Review

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Abstract

In recent years, breakthrough in the development of modelling techniques and impact analysis of composite materials subjected to high velocity has been made. The study methodically reviews the modelling techniques for the structural response of composite materials under high velocity. Although, report gives numerical model as widely used method, yet experimental test is always required to validate both analytical and finite element designs. The assessment shows that all modelling methods are suitable for application based on loading conditions of the composite structure. Lastly, the reference list provides databank for future researchers and engineers on composite structure subjected to high velocity impact.

Index terms— analytical approach, experimental method, finite element simulation, high velocity impact, composite materials.

1 Performance of Composite Structures Subjected

to High Velocity Impact -Review I. Introduction arbon fibre-reinforced composites are known for their high weight-specific stiffness and strength properties, which make them a preferred alternative in the material selection for modern lightweight structures in aeronautic and automotive engineering. However, these materials are susceptibility against impact loads. Internal damage formed in composite laminates spreads beyond the impacted area, and significantly reduces the strength and stiffness of the composite [1]. Composite materials response to impact loading and also the dissipation of the incident kinetic energy of the projectile is different when compared to metals. In traditional materials energy is absorb through elastic and plastic deformation which result in permanent structural deformation [2]. However, the capability of the composites to undergo plastic deformation is extremely limited as the resultant energy is frequently absorbed to create large zones for fracture with resultant reductions in both strength and stiffness [3].

Composite materials are extensively used in industrial applications such as aerospace, marine, locomotive and civil engineering structures due to their superior material properties. However, these materials tend to involve many microscopic damages including stiffness reduction due to impact which often leads to catastrophic failure. Currently, the extent of fiberreinforced composites applied in aircraft structures has become one of the most important targets making the advancement of modern structural design. Nevertheless the applications in aerospace industry, composites are increasingly used in other industries such as civil, sporting equipment, medical fields, automotive, railways and in marine vessels specifically for masts, hulls, desks and propellers. Unlike traditional materials, composites offer an endless array of design variations with flexibility accompanied by complications in modelling and analysis. This performance attracted transportation industries to develop structures replacing metallic material with the lighter structures. However, composite structures are poor to impact resistance owing to cyclic loading conditions, which results in inelastic behavior and poor damage resistance. Composite structures can develop local failures or exhibit local damage such as matrix cracks, fiber breakage, fiber-matrix debonds, and delaminations under normal operating conditions which may contribute to their failure.

High velocity impact is defined as local wave dominated response independent of boundary conditions ranging above 10 m/s, and characterized as dynamic events [4] with high speed and small mass. High velocity impact produces a short duration, steeply rising loading pulse when impacting the structure. It is dominated by inertial forces, wave propagation and changes in material stiffness, strength and fracture energy due to a high strain rate [5]. There are many parameters which influence the response of composite materials under high velocity impact, and these include: type, architectures and volume fraction of the reinforcement, laminate thickness, matrix system, projectile geometry and mass [6]. At high incident impact energies, target perforation may occur and the passage of the impactor naturally results in petalling, cracking and spalling. Although such damage reduce the load-bearing ability of the structure, its effects can generally be predicted using fracture mechanics principles [7].

In a high velocity impact, the response of the structural element is governed by the local behaviour of the material in the neighbourhood of the impacted zone; the impact response of the element being generally independent of its support conditions; and in most cases, impact test is carried out experimentally using a single stage gas gun. In recent years, researchers [8][9][10] have used sensors and transducers, however, residual velocity is difficult to measure as a result of shear plugs while other researchers have adopted a high-speed video cameras [11] due to its consistency and precision. As a result of focus on the impact response, it is important to understand the material's behaviour and the mode of assessment when subjected to impulsive loading.

Nowadays, composites are believed to have superior potential applications as the primary loadbearing structure in many industries, thus, studies on impact behaviour of carbon fibre composite have attracted much attention and become a hot research interest in the discipline of composite materials. This work is a bit of that endurance to establish numerical models capable for structural optimization in diverse engineering applications especially aeronautics and astronautics design. Therefore, the main objective of this paper is to review recent models used to analyze impact response of composite materials subjected to high velocity. Depending on the nature of the structure and the impact threshold, numerous studies have adopted analytical, experimental and numerical methods to analyze the structural behavior. On like metals, composite materials are anisotropic or orthotropic in nature and their mechanical behaviors under impact are complicated to predict, and therefore presents distinctive and demanding task for researchers and engineers to study in order to predict the impact response during static and dynamic loading conditions for safe used. This work endeavor is part of that endurance and aims to review the methodologies capable to predict structural performance in diverse engineering applications.

2 II. Methods of Analysis a) Experimental technique

Hosur et al. [15] conducted experimental study on response of stitched/unstitched woven fabriccarbon/epoxy composite laminates subjected to high velocity impact loading. The ensuing damage is characterized through ultrasonic NDE. Result of the study indicates that the damage is well contained within the stitch grid in the stitched laminates but higher for the unstitched laminates. Their studies also proved that ballistic limit increased with the increase in the thickness of the laminate; however, satin weave laminate exhibited higher ballistic limits in most of the cases.

Garcia-Castillo et al. [16] examined the damage in preloaded glass/vinylester composite panels subjected to high-velocity impacts. In their study, three representative structural cases (no, uniaxial and biaxial loadings) was analyzed. The result shows that the damage area was localized in the center of the panel; and qualitatively the damage area was largest on the non-loaded laminate of impact velocity of 136 m/s followed by 130m/s velocity uniaxial loading with the least being the 98m/s impact loading of the biaxial laminate. The study reveals that the impact energy and damage area was greater in the non-preload laminates than in the uniaxial and biaxial preloaded laminates. This difference occurs due to the increment of effective stiffness in panels subjected to membrane loads, which decreases the displacement of the panels, and accordingly reduces the damage area. This phenomenon is more significant at the perforationthreshold energy, where the bending of the panels is the greatest. High velocity impact response of sandwich structure composite laminated plates, Kevlar-29/epoxy and 60 61-T6 aluminium was experimentally investigated by [17] using a nitrogen gas gun. Adopting the same approach, high velocity projectile impact through different thickness of polyurea coated AA5083-H116 aluminium alloy plates was assessed by [18] .

Jabbar et al. [19] presented experimental study to compare the mechanical and ballistic performance of composites reinforced with single-layer and double-layer inter-locked woven fabrics low and high velocity impacts. The energy absorption and mechanical failure behavior of composites during the impact event were found to be strongly affected by the weave design of the reinforcement. The composites reinforced with doublelayer interlocked woven fabrics were found to perform better than those comprising single-layer fabrics in terms of impact energy absorption and mechanical failure. Similarly, Sultan [3] prescribed a study to examine the effect of thickness on fiber glass reinforced epoxy matrix subjected to high velocity impact loading. Their results show that the mechanical properties, damage characterization and impact resistance of type C-glass/Epoxy 600 g/m 2 possess better toughness, modulus and penetration compared to type C-glass/Epoxy 200 g/m 2 . Moreover, as the plate thickness increases, the maximum impact load and impact energy increases relatively. The result clearly reveals that impact damage was in the form of perforation, fiber breakage and matrix cracking. Lahuerta et al. [12] used an experimental technique to measure the delamination length in mode I tests based on video image processing. A nondimensional formulation of an analytical model proposed in a previous work of García Castillo et al. [13]

was redeveloped by [14] based on energy criteria to study the ballistic behaviour of composite plates made from woven laminates of E-glass fibers. This model allows for estimation of the residual velocity of the projectile, the ballistic limit, the energy absorbed by different mechanisms during the penetration of the laminate, and the contact time between the projectile and the laminate. Good agreement was found for residual velocities, contact time and ballistic limit for two geometry ratios.

Sabet et al. [20] presented experimental study on high velocity impact performance of glass reinforced polyester (GRP) resin composite plates with different type of reinforcement between the velocity range of 80 to 160 m/s. Result shows higher ballistic limit velocity (velocity at which samples fully penetrated the target plates with zero residual velocity) for 3 mm GRP plates with cross-ply unidirectional reinforcement followed by unidirectional reinforcement and plain weave, the plates with satin weave and chopped strand mat (CSM) reinforcements were almost in same level. The report added that thicker specimens (6 mm), plates with plain weave reinforcement showed better ballistic performance towards sharp tipped conical projectile impact, followed by cross-ply unidirectional, satin weave, unidirectional and CSM reinforced plates. Experimentally, the study reveals that the ballistic limit velocity for all specimens correlate well with estimated ballistic limit values obtained in full perforation tests. Findik et al. [21,22] have investigated experimental study on impact performance of some polymer-based composites and observed the contact mechanism as well as dynamic response of composite laminates. Pol et al. [23] performed experimental study on the influence of nano-clay Closite 30B on ballistic impact behavior of 2D woven E-glass/epoxy laminated composites.

The standard material characterization under compression and fracture modes was assessed by [24] under experimental study of high velocity impact fracture of ice. The failure of fiber reinforced thermoplastic composites (polypropylene made of hybrid E-glass/PP yarns) was investigated under medium and high velocity impact loading conditions by electromagnetic and acoustic emission signal measurements [25].

Hazell et al. [26] presented experimental study on the response of a bonded carbon-fiber-reinforced plastic composite panel to impact, penetration, and perforation by a high-velocity steel sphere. Hou et al. [27] identified and discussed the ballistic performance, quasi-static and impact perforation of metallic sandwich structures with aluminum foam and studied the effects of several key parameters as impact velocity, skin thickness, thickness, density of foam core, and projectile shapes on the ballistic limit and energy absorption of the panels during perforation of impact loading.

To elucidate the penetration and failure mechanisms, an experimental test using the JH-1 ceramic model of the projectile penetrating into a silicon carbide-faced polycarbonate is implemented in the hydro-code Autodyn-2D [28]. Übeyli et al. [29] have experimentally studied the ballistic behavior of laminated composite having alumina front and dual phase steel backing layers using 7.62 mm armor piercing (AP) projectiles under normal impact. The results showed that utilization of a 6 mm thick alumina front layer which is bonded to dual phase steel enhanced the ballistic resistance of the dual phase steel remarkably.

A study of the high velocity impact response of thick composite plates under tensile preload using a glass sphere projectile and an impact velocity is presented in [30], where less delaminations compared to the unloaded case are obtained under tensile preloads. Ballistic impact tests on thick woven Eglass/vinyl ester plates with compressive preload and variable velocities are performed by [31]. The authors report a detrimental effect on the residual strength of the composite plate.

3 b) Analytical study

Talib et al. [32] formulated analytical model to predict the performance of hybrid composite made of woven fiber Kevlar-29 and Al 2 O 3 powder/epoxy subjected to high velocity impact. The relationship between the ballistic limit with the thickness and energy absorption with thickness for Kevlar-29 fiber and Al 2 O 3 powder-reinforced composite materials was established. It was found that the proposed equation is suitable for this type of composite materials after comparing the behavior of the theoretical analyses with the experimental work. The experimental results showed good agreement compared with the theoretical work. The results indicate that the improvements in the performance target for bullet-proof applications are achieved.

Extensive parametric studies were carried-out on woven fabric thick composites and the energy absorption to predict the ballistic impact behavior of thick composites [33,34]. Also, a normal impact and perforation of conically-tipped hard steel cylinders was done on laminated Kevlar-29/polyester targets and pneumatic and powder guns, with a 12.7 mm barrel diameter are used for dynamic testing where ballistic An analytical formulation by Sheikh et al. [37] to predict the residual velocity of cylindrical projectiles under high velocity impacts on carbon epoxy laminates is investigated. Similarly, Udatha et al. **??**38] proposed analytical model to predict the performance of 3D woven composites under high velocity impact. For comparison, studies are also presented on the performance of twodimensional plain weave E-glass/epoxy composites. A good match is observed between the analytical predictions and experimentally obtained limit velocities for complete penetration. It is observed that limit velocity for complete penetration for three-dimensional woven composite is higher than that of two-dimensional plain weave composite.

Mishra et al. [39] formulated mathematical model based on theory of single yarn impact and implemented in MATLAB code to calculate the energy absorption and strain induced in the Kevlar and leather Performance of Composite Structures Subjected to High Velocity Impact -Review limits, terminal velocities and perforation are determined on target plates [35,36]. layers composites under high velocity impact. Results of the study shows that the stored energy increases and strain decreases with increase in impact time due to initially high kinetic energy utilizing of impactor for deformation than the absorbed in layers. As the impact time increases, tendency of deformation reduces and energy absorption improves. Again, the strain energy is high at the time of impact inception, due to kinetic energy of impactor is more than the energy absorbing capacity of layers which results in maximum damage of the layers; and the cone area developed in the Kevlar layer is more in comparison to leather layer has absorb more energy than leather layers. The study concludes that outcome of the results may be used as preliminary design tool for an assembly of rigid and semi-rigid materials in an armor system to reduce the experimental cost and time.

Ravi kumar et al. [40] presented analytical method to predict the compressive strength at high strain rate of 5000 s -1 loading of a typical woven fabric Eglass/epoxy composite L2R. The result is compared with the experimental tests using compressive split Hopkinson pressure bar apparatus, which observed that the compressive strength is enhanced at high strain rate loading compared with that at quasi-static loading.

Pernas-Sánchez et al. [41] proposed a simplified analytical model of carbon/epoxy tape quasiisotropic laminates to assess the different energy absorption mechanisms and predict the residual velocity of the projectile subjected to high velocity impacts. The model is validated by experimental test using destructive and non-destructive techniques.

Hossein et al. [42] studied the variation of the ballistic limit with areal density in a woven fabric made from Kevlar fibers. The model allows variation of spacing between laminas in order to study their effect on the ballistic limit. Again, the models based on energyconservation laws consider that the kinetic energy of the projectile at impact should be consumed during the perforation process by the elastic deformation of the panel, by the failure process of the laminate (which includes several mechanisms), by friction and heating of the laminate, and by accelerating the panel after impact [14].

Garc´?a-Castillo redeveloped an energy model based on the proposals of Naik, et al. [43] to study laminate plates subjected to ballistic impact with and without in-plane preloads [44,45]. The authors' model assumes that the plate absorbs the energy by three mechanisms: the elastic deformation of the fibers, the acceleration of the plate, and the generation of damage in the laminate. This damage may be due to the failure of fibers, delamination, and matrix cracking. This model is later used in a non-dimensional formulation to analyze the influence of several ratios in the ballistic behavior of thin laminates [46]. Fatt et al. [47] presented analytical solution to predict the residual velocity of a hemispherical-nose cylindrical projectile impacted on a composite sandwich panel at high velocity range of 75-325m/s. The analytical approach was mechanistic without any detailed account of progressive damage due to delamination and debonding but changes in the load-bearing resistance of the sandwich panel due to failure and complete loss of resistance from the face sheets and core during projectile penetration. The study indicated that the predicted transient deflection and velocity of the projectile and sandwich panel compared fairly well with results from finite element analysis. Again, analytical predictions of the projectile residual velocities were found to be in good agreement with experimental data found in literature.

Using an existing model [48], Feli and Pour [49] presented a new analytical model for perforation process of composite sandwich panels with honeycomb core subjected to high-velocity impact of cylindrical projectile. The redefined model is validated by comparing with [48] experimental tests and numerical model. A good agreement between the residual velocity of projectile in the new analytical model and experiment tests was established.

Mamivand et al. [50] developed analytical technique for the ballistic behaviour of 2-dimensional (2D) woven fabric composites. Similarly, Feli and Asgari [51] have presented analytical approach for perforation of ceramic/multi-layer woven fabric targets by blunt projectiles. This model was used to model back-up woven-fabric material and deformation of yarns during perforation where the kinetic and strain energy of yarns ware determined. Feli et al. [52] developed analytical model and FE simulation based on FE code in LS-DYNA for normal penetration of cylindrical projectiles onto the ceramic-composite targets. Liaghat et al. [53] presented analytical technique to determine the ballistic limit velocity of metallic honeycombs impacted by cylindrical projectiles. This method is based on the assumption that the total kinetic energy of the projectile is dissipated in folding and crushing of honeycomb, tearing of cell walls, forming and shearing of the plug.

López-Puente et al. [54] formulated analytical application to predict residual velocity after the impact onto a thin carbon/epoxy woven laminate. Their model considers three different energy absorption mechanisms for the laminate. The study used experimental impact test to validate the model and the results clearly shows a very good correlation between the results obtained from both experimental and numerical simulations in literature.

A non-dimensional formulation of an analytical model proposed in a previous work of García Castillo et al. [13] was redeveloped by [14] based on energy criteria to study the ballistic behaviour of composite plates made from woven laminates of E-glass fibers.

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4 c) Finite element method

A numerical model with appropriate erosion criteria for impact analysis of hybrid-fiber engineered cementitious composites (ECC) panels using LS-DYNA commercial software under high velocity is investigated by [55]. The study shows that the tensile stress-strain relationship of the developed numerical model compared with the experimental test in reference [56] is in good agreement.

Prakash et al. [57] developed FE model to study the influence of adhesive thickness on high velocity impact (HVI) performance of ceramic (Al 2 O 3 -99.5)/aluminum (Al5083 H116) composite laminate through a detailed numerical investigation using the AUTODYN software platform. The result of the study discloses that interface layer plays a significant role in the impact performance. The result is validated by experimental analysis for optimum designs of the target plates. Park et al. [58] performed numerical analysis using the commercial software tool LS-DYNA on high velocity impact of shear thickening fluids (STF) impregnated Kevlar fabric. The simulation results are in good agreement with empirical data obtained. The empirical and numerical study on the energy absorption characteristics of neat Kevlar and STF impregnated Kevlar fabrics suggest a positive effect by the STF impregnation on the energy absorption.

Pernas-Sánchez et al. [59] developed finite element model to predict the behavior of composite unidirectional laminates under high velocity impact. The numerical model is validated by C-Scan images which exhibit very good correlation with reference to penetration and the damaged area. Wang et al. [60] conducted FE analysis on CFRP laminates subjected to high velocity impact. The predicted numerical results are validated by experimental measurement; and the study shows that thin CFRP laminates have higher energy absorbing efficiency (EAE) under higher velocity (energy) while thick CFRP laminates have higher EAE under lower velocity (energy) impact. The energy absorbing efficiency comparison shows that impact velocity range of EAE-CFRP laminates is higher than that of stainless-steel. Therefore, CFRP laminates are seen as a potential advantage to substitute the metal plates in higher velocity impact resistance structures.

Ivañez et al. [61] formulated a user material VUMAT subroutine and implemented into ABAQUS/Explicit finite element platform to predict the high-velocity impact response of sandwich plates. The accuracy of the finite-element model is determined by comparing experimental data with numerical predictions in terms of ballistic limit and residual velocity. Satisfactory agreement with the experimental results was established. The comparison of the damaged area in sandwich and spaced plates revealed that the suppression of the foam core in the sandwich structure affects the size of the damaged area. Buitrago et al. [48] formulated a model and implemented into ABAQUS/Explicit through user-written VUMAT subroutines finite element to predict the behaviour of sandwich panels made of carbon/epoxy laminate skins with aluminum honeycomb core under high-velocity impacts. The model is validated with experimental tests by comparing numerical and experimental residual velocity, ballistic limit and contact time.

Heimbs et al. [62] have carried out an experimental and numerical study of the influence of tensile and compressive preloading impact on the performance of carbon/epoxy plates at high velocity.

Ultrasonic C-scans and micrographs are used for the post-test damage inspection, where matrix cracking and delaminations are observed as the major impact damage modes. Tensile preloading is found to reduce the extent of delaminations, while compressive preload increased the extent of delaminations resulting from a higher bending deflection of the impact plate. The study shows that preloading has an influence on the impact response of laminated composite plates and is relevant in the structural design analyses.

Silva et al. [63] presented experimental and numerical application to predict the ballistic impact on composite laminated plates reinforced with Kevlar-29/Vinylester. The analysis is performed using a commercial code based on finite difference hydrocode AUTODYN and values obtained are compared with the experimental data to evaluate the performance of the simulation. Good correlation between numerical simulation and experimental results is achieved for deformation and damage of the laminates. Tham et al. [64] conducted a combined experimental and 3D dynamic nonlinear finite element (FE) approach to study damage in composite beams subject to ballistic impact. The influence of tensile and compressive preloads on the soft body impact behaviour of composite laminates has been studied experimentally and numerically in [65], where the researchers used gelatine projectile as a substitute material.

Bürger et al. [66] formulated a model based on Lagrangian and implemented into an explicit solver in the commercial FEA software ABAQUS/Explicit to simulate the ballistic impact of an armor-piercing projectile in hybrid ceramic/fiber reinforced composite armor. The ballistic limit prediction velocity shows that global damage and residual velocity are very accurate when experimentally compared. Sastry et al. [67] developed numerical model and implemented into the commercial software ABAQUS/Explicit to study the effect of ballistic impact on the composite plate madeup of woven fabric CFRP, the E-glass/epoxy and the Kevlar/epoxy for different ply stacking sequences. The result indicates that the Kevlar/epoxy absorbs a maximum kinetic energy of energy compared to the other the two materials. The numerical simulation provides quick estimation with good accuracy and reliability as compared to experimental results.

Sevkat et al. [68] presented a combined experimental and numerical approach to study the ballistic impact response of S2-glass fiber toughened epoxy composite beams using a high speed gas gun. Again, a hybrid particle finite element algorithm for high velocity impact based on the Generalized Particle Algorithm (GPA) is formulated [69][70][71] and compared to the other computation algorithm.

Mohotti et al. [72] formulated a bird strike-like projectile simulation using explicit finite element code in LS-DYNA to investigate the behaviour of multi-layered composite plate coated with polyurea and aluminium alloys under high velocity impact. The study shows that the application of polyurea coatings resulted in a higher residual velocity reduction per unit areal density than aluminium alloys. This indicates the feasibility of polyurea to be utilised in layered composite armour systems in mitigating ballistic threats.

Kumar et al. [73] have numerically study the effect of impactor and laminate parameters on the impact response and impact-induced damages in graphite/epoxy laminated cylindrical shells using 3D finite element formulation. The numerical results compared with experimental data showed good correlation. Zhao and Cho [74] investigated the impactinduced damage initiation and propagation in the laminated composite shell under low-velocity impact. The study employed a three dimensional eight-node non-conforming element with Taylor's modification scheme to analysis the interlaminar stress distribution and damage propagation.

Ghosh and Sinha [75] developed a finite element model to predict the initiation and propagation of damage laminated composite plates under forced vibration and impact loads. Tarfaoui et al. [76] presented a FEA of static and dynamic tests on thick filament wound glass/epoxy tubes. The material characteristics of the models are validated to predict the static and dynamic elastic behavior. Kim et al. [77] have numerically proposed a damage model based on continuum damage mechanics for the progressive damage analysis of a composite structure. The damage model is implemented in the user material subroutine of the ABAQUS/Explicit program. The impact response and damage from the numerical analysis are comparable with results obtained through experimental test.

5 III. Concluding Remarks

This paper reviews the modelling techniques to analysis the impact response of composite structures subjected to high velocity. Three approaches; experimental, analytical and numerical methods were successfully employed to predict the impact behaviour. The report shows that numerous researchers assessed the impact behaviour of composite edifice through experimental method due to the simplification of use and does not need detail parameter on actual damage mechanisms. But, this method is costly and difficult to extend towards more general loading conditions, where multi-axial stress conditions are imposed. Finite element simulations have been applied to structural analysis under high velocity impact loadings for accurate estimation of results under both static and dynamic conditions. On the other hand, computational cost is very high, which requires high performance computers to model complex impact events. Again, numerous researchers and engineers have applied analytical models due to low computational cost and time, and capable to define the physical behaviour of the composite materials. Noticeably, analytical formulations are only applicable to simple models. The report shows that all methods for analysis are suitable for application based on loading conditions of the composite material. Nonetheless, numerical simulation offers the most detailed information on the spatial and temporal distribution of damage during impact which is more flexible and powerful alternative and widely used compare to analytical formulations and experimental tests. [1] [2] [3]

[2]Performance of Composite Structures Subjected to High Velocity Impact -Review

[Razali et al.] , N Razali , Mth Sultan , F Mustapha , N Yidris , M R Ishak . (Impact Damage on Composite Structures-A Review)

[Alves et al.] , M Alves , C Chaves , R S Birch . (Impact on aircraft)

[Johnson et al. ()] 'A 3D combined particle-element method for intense impulsive loading computations involving severe distortions'. G Johnson , S Beissel , C Gerlach . *International Journal of Impact Engineering* 2015. 84 p. .

[Sevkat et al. ()] *A combined experimental and numerical approach to study and Technology*, E Sevkat , B Liaw , F Delale , B B Raju . 2009. 69 p. .

[Johnson et al. ()] 'A combined particle-element method for high-velocity impact computations'. G Johnson , S Beissel , C Gerlach . *Procedia Engineering* 2013. 58 p. .

[Mamivand and Liaghat ()] 'A model for ballistic impact on multi-layer fabric targets'. M Mamivand , G H Liaghat . *International Journal of Impact Engineering* 2010. 37 p. .

[Fatt and Sirivolu ()] 'A wave propagation model for the high velocity impact response of a composite sandwich panel'. Msh Fatt , D Sirivolu . *International journal of impact engineering* 2010. 37 p. .

[Feli and Pour ()] 'An analytical model for composite sandwich panels with honeycomb core subjected to high-velocity impact'. S Feli , Mhn Pour . *Composites Part B: Engineering* 2012. 43 p. .

[López-Puente et al. ()] 'An analytical model for high velocity impacts on thin'. J López-Puente , R Zaera , C Navarro . *CFRPs Global Journal of Researches in Engineering* 2007. 44 p. . (International Journal of solids and structures)

[Feli et al. ()] 'An analytical model for perforation of ceramic/multi-layered planar woven fabric targets by blunt projectiles'. S Feli , M H Yas , M R Asgari . *Composite Structures* 2011. 93 p. .

[Naik et al. ()] 'An energy-based model for ballistic impact analysis of ceramic-composite armors'. N K Naik , S Kumar , D Ratnaveer , M Joshi , K Akella . *International Journal of Damage Mechanics* 2012. p. 1056789511435346.

[Ravikumar et al. ()] 'Analytical and experimental studies on mechanical behavior of composites under high strain rate compressive loading'. G Ravikumar , J R Pothnis , M Joshi , K Akella , S Kumar , N K Naik . *Materials &Design* 2013. 44 p. .

[Johnson et al. ()] 'Another approach to a hybrid particle-finite element algorithm for highvelocity impact'. G Johnson , S Beissel , C Gerlach . *International journal of impact engineering* 2011. 38 p. .

[Naik and Doshi ()] *Ballistic impact behaviour of thick composites: Parametric studies. Composite structures*, N K Naik , A V Doshi . 2008. 82 p. .

[Findik and Tarim ()] *Ballistic impact efficiency of polymer composites. Composite structures*, F Findik , N Tarim . 2003. 61 p. .

[Hou et al. ()] 'Ballistic impact experiments of metallic sandwich panels with aluminium foam core'. W Hou , F Zhu , G Lu , D-N Fang . *International journal of impact engineering* 2010. 37 p. .

[Tham et al. ()] 'Ballistic impact of a KEVLAR® helmet: Experiment and simulations'. C Y Tham , Vbc Tan , H P Lee . *International Journal of Impact Engineering* 2008. 35 p. .

[Übeyli et al. ()] 'Ballistic impact performance of an armor material consisting of alumina and dual phase steel layers'. M Übeyli , H Deniz , T Demir , B Ögel , B Gürel , Ö Kele? . *Materials & Design* 2011. 32 p. .

[Tarim et al. ()] 'Ballistic impact performance of composite structures'. N Tarim , F Findik , H Uzun . *Composite Structures* 2002. 56 p. .

[Nair et al. ()] 'Ballistic impact performance of composite targets'. N S Nair , Cvs Kumar , N K Naik . *Materials & Design* 2013. 51 p. .

[Talib et al. ()] 'Ballistic impact performance of Kevlar-29 and Al 2 O 3 powder/epoxy targets under high velocity impact'. Ara Talib , L H Abbud , A Ali , F Mustapha . *Materials & Design* 2012. 35 p. .

[Bürger et al. ()] 'Ballistic impact simulation of an armour-piercing projectile on hybrid ceramic/fiber reinforced composite armours'. D Bürger , De Faria , AR , De Almeida , Sfm , De Melo , Fcl Donadon , MV . *International Journal of Impact Engineering* 2012. 43 p. .

[Liaghat et al. ()] *Ballistic limit evaluation for impact of cylindrical projectiles on honeycomb panels. Thin-Walled Structures*, G H Liaghat , A A Nia , H R Daghyani , M Sadighi . 2010. 48 p. .

[Zee et al. ()] 'Ballistic response of polymer composites'. R H Zee , C J Wang , A Mount , B Z Jang , C Y Hsieh . *Polymer composites* 1991. 12 p. .

[Maalej et al. ()] 'Behavior of hybridfiber engineered cementitious composites subjected to dynamic tensile loading and projectile impact'. M Maalej , S T Quek , J Zhang . *Journal of Materials in Civil Engineering* 2005. 17 p. .

[Sheikh et al. ()] 'Behaviour of multiple composite plates subjected to ballistic impact'. A H Sheikh , P H Bull , J A Kepler . *Composites Science and Technology* 2009. 69 p. .

[Astanin et al. ()] 'Characterising failure in textileof Composite Structures Subjected to High Velocity Impact'. V V Astanin , G O Shchegel , W Hufenbach , A Hornig , A Langkamp . *Review* 2014. 2012. 63 p. .

[Jabbar et al. ()] 'Comparison of mechanical and ballistic performance of composite laminates produced from single-layer and double-layer interlocked woven structures'. A Jabbar , Hasan Malik , M Hussain , T Zulifqar , A Tausif , M . *Polymer Composites* 2014. 35 p. .

[Kim et al. ()] 'Composite damage model based on continuum damage mechanics and low velocity impact analysis of composite plates'. E-H Kim , M-S Rim , I Lee , T-K Hwang . *Composite Structures* 2013. 95 p. .

[Garcia-Castillo et al. ()] 'Damage in preloaded glass/vinylester composite panels subjected to high-velocity impacts'. S K Garcia-Castillo , C Navarro , E Barbero . *Mechanics Research Communications* 2014. 55 p. .

[Ghosh and Sinha ()] *Dynamic and impact response of damaged laminated composite plates. Aircraft Engineering and Aerospace Technology*, A Ghosh , P K Sinha . 2004. 76 p. .

[Tarfaoui et al. ()] 'Dynamic response and damage modeling of glass/epoxy tubular structures: Numerical investigation'. M Tarfaoui , P B Gning , L Hamitouche . *Composites Part A: Applied Science and Manufacturing* 2008. 39 p. .

[Vaidya and Shafiq] *Dynamic response of navy relevant laminated and sandwich composites subjected to complex impact loads*, U K Vaidya , B Shafiq . p. .

[Kumar et al. ()] 'Effect of impactor parameters and laminate characteristics on impact response and damage in curved composite laminates'. S Kumar , B N Rao , B Pradhan . *Journal of Reinforced Plastics and Composites* 2007. 26 p. .

[Pol et al. ()] 'Effect of nanoclay on ballistic behavior of woven fabric composites: Experimental investigation'. M H Pol , G H Liaghat , F Hajiarazi . *Journal of Composite Materials* 2012. p. 0021998312449768.

[Pol et al. ()] 'Effect of nanoclay particles on the ballistic behavior of glass/epoxy composites-experimental investigation'. M H Pol , G H Liaghat , S Mazdak . *Journal Modares Mechanical Engineerimg* 2013. 13 p. .

[Sabet et al. ()] 'Effect of reinforcement type on high velocity impact response of GRP plates using a sharp tip projectile'. A Sabet , N Fagih , M H Beheshty . *International Journal of Impact Engineering* 2011. 38 p. .

[Wang et al. ()] 'Energy absorption efficiency of carbon fiber reinforced polymer laminates under high velocity impact'. B Wang , J Xiong , X Wang , L Ma , G-Q Zhang , L-Z Wu . *Materials & Design* 2013. 50 p. .

[Li and Zhang ()] 'Evolution and calibration of a numerical model for modelling of hybrid-fibre ECC panels under high-velocity impact'. J Li , Y X Zhang . *Composite Structures* 2011. 93 p. .

[Pernas-Sánchez et al. ()] 'Experimental analysis of normal and oblique high velocity impacts on carbon/epoxy tape laminates'. J Pernas-Sánchez , J A Artero-Guerrero , D Varas , J López-Puente . *Composites Part A: Applied Science and Manufacturing* 2014. 60 p. .

[Varas et al. ()] 'Experimental study of CFRP fluid-filled tubes subjected to highvelocity impact'. D Varas , R Zaera , J López-Puente . *Composite Structures* 2011. 93 p. .

[Combescure et al. ()] 'Experimental study of high-velocity impact and fracture of ice'. A Combescure , Y Chuzel-Marmot , J Fabis . *International Journal of Solids and Structures* 2011. 48 p. .

[Feli and Asgari ()] 'Finite element simulation of ceramic/composite armor under ballistic impact'. S Feli , M R Asgari . *Composites Part B: Engineering* 2011. 42 p. .

[Mishra et al. ()] 'High Velocity Impact Analysis of Kevlar Composite by MATLAB'. R R Mishra , Anv Kumar , S Rajesha . *Indian Journal of Advances in Chemical Science* 2014. 2 p. .

[Sultan et al.] 'High velocity impact damage analysis for glass epoxy-Laminated plates'. Mth Sultan , S Basri , Asm Rafie , F Mustapha , D L Majid , M R Ajir . *Trans Tech Publ* p. .

[Heimbs et al. ()] 'High velocity impact on preloaded composite plates'. S Heimbs , T Bergmann , D Schueler , N Toso-Pentecôte . *Composite Structures* 2014. 111 p. .

[Udatha et al. ()] *High velocity impact performance of three-dimensional woven composites. The Journal of Strain Analysis For Engineering Design*, P Udatha , Cvs Kumar , N S Nair , N K Naik . 2012. p. 0309324712448578.

[Ramadhan et al. ()] 'High velocity impact response of Kevlar-29/epoxy and 6061-T6 aluminum laminated panels'. A A Ramadhan , Ara Talib , Asm Rafie , R Zahari . *Materials & Design* 2013. 43 p. .

[Heimbs and Bergmann ()] 'High-velocity impact behaviour of prestressed composite plates under bird strike loading'. S Heimbs , T Bergmann . *International Journal of Aerospace Engineering* 2012. 2012.

[García-Castillo et al. ()] 'Impact behaviour of preloaded glass/polyester woven plates'. S K García-Castillo , S Sánchez-Sáez , J López-Puente , E Barbero , C Navarro . *Composites Science and Technology* 2009. 69 p. .

[Ali et al. ()] 'Impact Resistance of Armor Composite Made of Kevlar29 and Al2O3 Powder'. A Ali , L H Abbud , Ara Talib , F Mustapha . *Materials Testing* 2012. 54 p. .

[Hazell et al. ()] 'Impact, penetration, and perforation of a bonded carbonfibre-reinforced plastic composite panel by a highvelocity steel sphere: an experimental study'. P J Hazell , G J Appleby-Thomas , G Kister . *The Journal of Strain Analysis for Engineering Design* 2010. 45 p. .

[Prakash et al. ()] 'Influence of adhesive thickness on high velocity impact performance of ceramic/metal composite targets'. A Prakash , J Rajasankar , N Anandavalli , M Verma , N R Iyer . *International Journal of Adhesion and Adhesives* 2013. 41 p. .

[García-Castillo et al. ()] 'Influence of areal density on the energy absorbed by thin composite plates subjected to high-velocity impacts'. S K García-Castillo , S Sánchez-Sáez , E Barbero . *The Journal of Strain Analysis for Engineering Design* 2012. p. 0309324712454996.

[Lahuerta et al.] 'Measuring the delamination length in static and fatigue mode I tests using video image processing'. F Lahuerta , T Westphal , Rpl Nijssen , F P Van Der Meer , L J Sluys . *Composites Part B: Engineering*

[Kaw ()] *Mechanics of composite materials*, A K Kaw . 2005. CRC press.

[Fatt et al. ()] *Modeling Blast and High-Velocity Impact of Composite Sandwich Panels. Major Accomplishments in Composite Materials and Sandwich Structures*, Msh Fatt , L Palla , D Sirivolu . 2010. Springer. p. .

[Schueler et al. ()] *Modeling of High Velocity Impact on Preloaded Composite Panels*, D Schueler , N Toso-Pentecôte , H Voggenreiter . 2011.

[Abrate ()] *Modeling of impacts on composite structures. Composite structures*, S Abrate . 2001. 51 p. .

[Wisnom ()] 'Modelling discrete failures in composites with interface elements'. M Wisnom . *Composites Part A: Applied Science and Manufacturing* 2010. 41 p. .

[Buitrago et al. ()] *Modelling of composite sandwich structures with honeycomb core subjected to highvelocity impact. Composite structures*, B L Buitrago , C Santiuste , S Sánchez-Sáez , E Barbero , C Navarro . 2010. 92 p. .

[García-Castillo et al. ()] 'Nondimensional analysis of ballistic impact on thin woven laminate plates'. S K García-Castillo , S Sánchez-Sáez , E Barbero . *International Journal of Impact Engineering* 2012. 39 p. .

[Pernas-Sánchez et al. ()] 'Numerical analysis of high velocity impacts on unidirectional laminates'. J Pernas-Sánchez , J A Artero-Guerrero , J Z Viñuela , D Varas , J López-Puente . *Composite Structures* 2014. 107 p. .

[Ivañez et al. ()] *Numerical modelling of foam-cored sandwich plates under high-velocity impact. Composite structures*, I Ivañez , C Santiuste , E Barbero , S Sánchez-Sáez . 2011. 93 p. .

[Park et al. ()] 'Numerical simulation and empirical comparison of the high velocity impact of STF impregnated Kevlar fabric using friction effects'. Y Park , Y Kim , A H Baluch , C-G Kim . *Composite Structures* 2015. 125 p. .

[Silva et al. ()] 'Numerical simulation of ballistic impact on composite laminates'. Mag Silva , C Cisma?iu , C G Chiorean . *International Journal of Impact Engineering* 2005. 31 p. .

[Zhao and Cho ()] 'On impact damage of composite shells by a low-velocity projectile'. G Zhao , C Cho . *Journal of composite materials* 2004. 38 p. .

[Zhang and Li ()] 'On the comparison of the ballistic performance of 10% zirconia toughened alumina and 95% alumina ceramic target'. X F Zhang , Y C Li . *Materials & Design* 2010. 31 p. .

[Patel et al. ()] 'Penetration of projectiles in composite laminates'. B P Patel , S K Bhola , M Ganapathi , D P Makhecha . *Defence Science Journal* 2004. 54 p. .

[García-Castillo et al. ()] *Perforation of Composite Laminate Subjected to Dynamic Loads. Dynamic Failure of Composite and Sandwich Structures*, S K García-Castillo , S Sánchez-Sáez , C Santiuste , C Navarro , E Barbero . 2013. Springer. p. .

[Hosur et al. ()] 'Performance of stitched/unstitched woven carbon/epoxy composites under high velocity impact loading'. M V Hosur , U K Vaidya , C Ulven , S Jeelani . *Composite Structures* 2004. 64 p. .

[Mohotti et al. ()] 'Polyurea coated composite aluminium plates subjected to high velocity projectile impact'. D Mohotti , T Ngo , P Mendis , S N Raman . *Materials & Design* 2013. 52 p. .

[García-Castillo et al.] *Response of pre-loaded laminate composite plates subject to high velocity impact*, S K García-Castillo , S Sánchez-Sáez , E Barbero , C Navarro . EDP sciences. p. .

[Wan et al. ()] 'Shielding performances of the designed hybrid laminates impacted by hypervelocity flyer'. H Wan , S Bai , S Li , J Mo , S Zhao , Z Song . *Materials & Design* 2013. 52 p. .

[Sastry et al. ()] 'Studies on ballistic impact of the composite panels'. Ybs Sastry , P R Budarapu , Y Krishna , S Devaraj . *Theoretical and Applied Fracture Mechanics* 2014. 72 p. .

[Zhou et al. ()] 'The perforation resistance of sandwich structures subjected to low velocity projectile impact loading'. J Zhou , Z W Guan , W J Cantwell . *Aeronautical Journal* 2012. 116 p. 1247.

[Poe and Jackson ()] 'The use of impact force as a scale parameter for the impact response of composite laminates'. C Poe , W C Jackson . *Technology and Research* 1993. 15 p. . (Journal of Composites)