Onder A, O'Neill C, Robinson M.

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In: 6th Transport Research Arena (TRA2016). 2016, Warsaw, Poland: Elsevier.

DOI link to article:

http://dx.doi.org/10.1016/j.trpro.2016.05.301

Date deposited:

12/05/2016

Available online at www.sciencedirect.com

ScienceDirect

Transportation Research Procedia 14 (2016) 595 – 604

Transportation Research Procedia

www.elsevier.com/locate/procedia

6th Transport Research Arena April 18-21, 2016

Flying ballast resistance for composite materials in railway vehicle carbody shells

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Abstract

This paper describes a simplified practical approach to the impact damage assessment of flying ballast or debris in composite materials, which could potentially be used for passenger rail vehicles. With the development of high-speed lines in order to guarantee the safety of primarily the driver and passengers, the vehicle body shell must be strong enough to resist the penetration of these types of objects into the vehicle. Currently the EN12663 standard has insufficient information on missile impact requirements for car bodies. Using the requirements of British Railway Group Standard GM/RT2100, GFRP composite material was analyzed in both static and dynamic events. Impact events at high velocities (V>50 m/s) lead to difficulties in testing due to the requirements for specific and expensive equipment and safety issues in the test application process. The simpler assessment and testing method described in this paper aims to provide a more cost effective, less time consuming, easily applicable method, with accurate results compared to existing methods. Previous research found that high-velocity impact behavior of composite materials can be mimicked by quasi-static punch tests (QSP). In this study, QSP tests were performed with E-glass/polyester composite laminates and FE simulations were carried out to match the experiments. The resulting numerical material and modelling data was used to simulate high velocity impact cases to assess the response of the material and to determine the connection between static and dynamic cases.

Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)

Keywords: composite materials; high-speed impact; railway vehicle

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Peer-review under responsibility of Road and Bridge Research Institute (IBDiM)
doi:10.1016/j.trpro.2016.05.301

1. Introduction

The interest in using composite materials for structural applications in many different industries has increased significantly in the past decades. Being lightweight (i.e. high strength/stiffness-to-weight ratio) as well as having other various advantageous properties such as heat/fire/corrosion resistance, cost-effectiveness, freedom of manufacture in accordance with the critical load paths, numerous combinations of fibre-matrix, etc. are making composites greatly attractive to use in almost every field.

Nomenclature

CF	circular flat
FE	finite element
GFRP	glass fibre reinforced plastic
H	hemispherical
HVI	high velocity impact
QSP	quasi-static punch
SPR	span to punch diameter ratio

Although they are not entirely new materials for the railway sector, it can be said that the sector itself is rather underdeveloped in terms of composite materials use compared to the marine, automotive, and aviation industries, which have magnificent huge-scale examples of composite material use. In the railway industry, composites have been in use since the 1980s for seats, carriage doors, cab fronts, as well as overhead structures (Batchelor and Wilson, 1984). However, application in primary load bearing structures is rather new, with a few good examples such as the Korean Tilting Train – TTX (Kim et al., 2007), and the Kawasaki efWING bogie with carbon fibre reinforced plastic (CFRP) leaf springs (URL1). There is a tendency in the railway sector towards using more lightweight materials in order to achieve a more energy efficient transportation, through both practical examples (Robinson et al., 2012) and with projects focusing on the modification of regulations. An example is the REFRESCO project, funded by the European Commission (EC), with the aim to generate regulations for implementing lightweight materials into railway rolling stock (REFRESCO, 2013). The reasoning behind the necessity for modification to regulations is basically due to the differences in mechanical responses of composites compared to metallic (conventional) materials and the anisotropic nature of composites requires detailed and careful analysis in many aspects before putting them to long term use. These aspects should include both material based analysis and application specific analysis since this pool of knowledge would encourage manufacturing and operational bodies to take appropriate action when using alternative lightweight materials. In addition, the specific changes that come with the technological improvements in the sector itself might also require the re-check of current regulations even if it is for the same materials. For example, and particularly in the last two decades, in order to achieve a more efficient transportation by decreasing traveling times, the operating speed of passenger vehicles has increased greatly. This in turn affects the interacting sub-systems such as infrastructure, braking systems, and safety systems. Safety is always the most important aspect of any transportation system including railways. One of the safety requirements for a rail vehicle relates to missile protection, which indicates that the carbody shell should not allow a flying object to penetrate and enter the vehicle. Flying objects can be any solid object or debris around the track that might become airborne – for example caused by snowfall under a train, aerodynamic forces generated by passing trains, or by deliberate actions of individuals towards moving vehicles. This requirement is mentioned in GM/RT-2100 British Railway Group Standard, but there is no clear information on this specific requirement in European Code EN12663 and both of these standards relate to metallic based materials. The present study will analyze the impact damage phenomena for composites, which have the potential to be used in car body shells, in parallel with the relevant standards requirement.

Mechanical behavior and damage mechanisms of composite materials can be very complex due to their direction dependency, the interactions between fibre-matrix phases and the behavior of the interface in between. Particular interest was given to impact responses by many researchers for years, with focus on different aspects such as the effects of impact speed, i.e. low-intermediate-high velocity ((Naik and Doshi, 2008), (Vaidya, 2011)), impacting geometry (Gellert et al., 2000), fibre/matrix type and different structure configurations, i.e. laminated or sandwich composites (Reid and Wen, 2000), damage progression ((Yen, 2002), (Xiao et al., 2007)), etc. by experimental and/or numerical effort. However, there are difficulties in both experimental and numerical simulations for these types of dynamic events as it requires specific test setup or modelling aspects.

The difficulty in experimental effort is mainly dependent on the application level, i.e. either low or high velocity testing. While low-velocity (or energy) impact tests can be carried out with drop weight test rigs which can be reachable most of the time, the situation is not that easy for high-velocity testing. This type of test requires extensive test rigs with visual output systems (high-speed cameras), velocity measuring systems, data acquisition and filtering systems, and specialized personnel to carry out the tests in a safe and secure environment. Hence the investment for this type of testing is very expensive making it difficult to achieve.

To accurately simulate an impact event with composites a considerable amount of modelling input about the composite material is required by the software program, and the software itself should have certain capabilities such as progressive damage modelling or anisotropic material modelling, depending on the application. Lately there have been some quite accurate simulations carried out by researchers ((Yen, 2002), (Xiao et al., 2007), (Gama and Gillespie, 2011)) with commercial software such as LS-DYNA, ABAQUS, ANSYS (AUTODYN), etc. In the present study ANSYS Workbench and AUTODYN was used to simulate the impact response of composite materials.

In recent years, research revealed that the damage similarities of high-velocity impact events of composite laminates were similar to those of quasi-static punch (QSP) tests with the same boundary conditions ((Gama and Gillespie, 2008), (Sun and Potti, 1996)). QSP tests are the deliberate penetration of samples by a punch tip at slow crosshead displacement rates (1, 2, 3 mm/min etc.). Gama and Gillespie specifically proposed a methodology to identify the ballistic limit of a laminated composite by using QSP tests (Gama and Gillespie, 2008). Inspired by their work, the present study analyses the impact responses of E-glass/polyester composite laminates with QSP testing, as an alternative to expensive high-velocity impact testing and suggest a simple testing method and concept for the impact assessment of composites in railway rolling stock.

1.1. Analysis and discussion on Missile Protection Requirement

British Railway Group Standard GM/RT-2100 describes the penetration resistance of a rail carbody against striking objects from the outside. According to this regulation, all forward facing surfaces should have a penetration resistance against a cylindrical aluminum alloy projectile in 94 mm diameter with a hemispherical tip, weighting 1 kg, and traveling at a maximum speed of vehicle operating speed plus 160 km/h. Specifically, this requirement is involved in the forward facing surfaces such as cab front, which should be tested as if it were in actual operating conditions, i.e. rake angle of the front cab. As the testing procedure, presented in this paper, was performed perpendicular to the composite laminate samples, this positioning can be considered as the worst case scenario for the impacted structure since the cab fronts have an angle with respect to the vertical direction.

When compared with the high velocity or ballistic impact research in the literature, the relevant projectile dimensions are significantly larger and the mass is quite heavier. Considering the information obtained from Ingleton (Ingleton, 2005), the main motive behind this specification might be the violence against rolling stock by individuals. According to his information, around 87% of the damaging missile strikes against windscreens and drivers during the years 1996/97 are based on vandalism acts of humans, and this type of attack has increased in later years (Ingleton, 2005). This is therefore generally considered as the main reason why the impactor is so large. The purpose of mentioning this specific standard in this work is basically to set this standard as a guideline for a different approach to impact behavior of composite materials, using relevant and necessary information, and to point out that penetration resistance against flying objects is an important issue for safety in rail vehicles, which has an actual requirement for its assessment. Besides, if composite materials were to be used in railway rolling stock in the future, it is likely that an assessment of the impact events on composites would be essential as these types of materials renowned for being susceptible to impacts events. For example visually undetectable internal damage such as matrix cracking, fibre breakage and delamination may greatly reduce the structure’s strength, leading to unexpected catastrophic failure. In addition, it has been reported by Saussine et al. that with the improvement of high speed lines, flying ballast has become an important phenomenon that cannot be neglected (Saussine et al., 2011).

One may argue that an average ballast size and weight cannot be compared with the impactor in the regulation, and the ballast strike phenomenon is basically related with underframe (floor) structure due to the snowfall induced ballast movement. Nevertheless, ballast is considered as a flying object representative in this study, which is one of the closest solid objects to an operating train. Even when the underframe structure is of concern, the velocity of the striking ballast is more or less equal to the speed of the train, and considering the operating speed of passenger rail vehicles in Europe (up to 300 km/h), impacting velocity can be considered as high velocity. In this study, a reasonable sized impactor will be mentioned and further decisions will be made in the future. In short, the essence and aim of this present study was to find a more simple new approach to the assessment of impact response for composite materials.

2. Experimental details

2.1. Fixture details

The QSP tests were carried out with 2 sets of custom steel fixtures which hold the specimens in place and enable penetration deformation by a central hole, and two different punch tips, i.e. cylindrical circular flat tip (CF) and cylindrical hemispherical tip (H) (Fig. 1). The combination of fixtures and punch tips facilitates the generation of two different span-to-punch ratios (SPR), i.e. 1.2 and 4.1. Previously used by a number of authors ((Sun and Potti, 1996), (Potti and Sun, 1997), (Erkendirci and Haque, 2012), (Gama and Gillespie, 2008), (Xiao et al., 2007)), this ratio distinguishes the specimen's deformation behavior. Higher ratios enable bending dominated deformation, while lower ratio results in shear dominated deformation response, which is related with the low or high velocity deformation mechanisms. Higher velocity impacts exhibit shear dominant behaviour, while lower velocity impact exhibits bending dominated. The dimensions of the fixture was 240×240 mm side length with a 25 mm thick supporting plate and a 10 mm thick cover plate on top. 12 M8 bolts were used to prevent slippage during the tests. The diameter of the center hole was 106 mm for the bigger fixture and 31.62 mm for smaller fixture. Both circular flat (CF) and hemispherical (H) tips were 25.4 mm in diameter. Custom fixtures were used with the Shimadzu tensile test rig (100 kN max load) with a crosshead displacement rate of 2 mm/min. Stress-strain, force-displacement graphs, and energy values were obtained from Trapezium software.

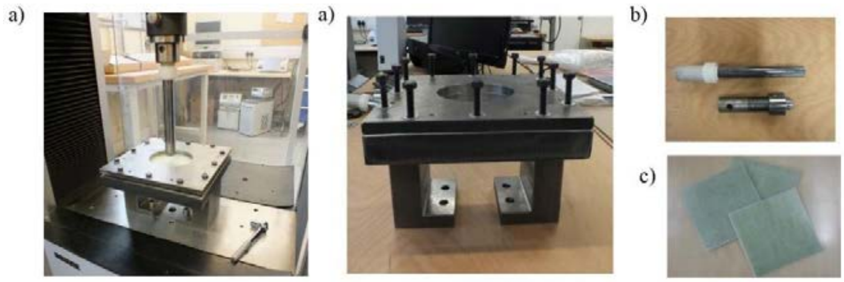

Fig. 1. Fixture and specimens used in the experiments; a) steel fixture; b) punch tips; c) GFRP samples.

2.2. Specimen details

Glass fibre reinforced plastic (GFRP) plates were used in the present study. E-Glass fibre/polyester resin plates were manufactured by hand lay-up method, using plain weave glass fibre fabric, oriented at 0° and 90° degree in longitudinal and transverse directions, respectively. Fibre volume fraction (ν_f) of the composite is calculated as 60% through mass fraction method. The dimensions of each square plate was 200×200 mm with a thickness of 6 mm. The reasons for using the E-glass/polyester were its cost effectiveness, i.e. being one of the most affordable fibre-matrix combinations, and also the compatibility with the rail industry. Due to the limited time constraints and availability of material characterization tools, in-plane material properties were obtained, in this instance, through physical testing in accordance with ISO-527-4 standard. Furthermore additional properties were used as a baseline from a very close configuration of a previous study (Tasdemirci et al., 2011), and then simulations were performed to obtain the real material properties of E-glass/polyester GFRP. Table 1 shows the material properties used in this research.

Table 1. E-glass/polyester GFRP material properties *(*obtained from (Tasdemirci et al., 2011)).*

Young's Modulus – E (GPa)	Poisson's Ratio – ν	Shear Modulus – G (GPa)*
E_1= 12,895	ν_{12}= 0.08	G_{12}= 1.79
E_2= 12,895	ν_{23}= 0.14	G_{23}= 1.52
E_3= 8,000*	ν_{31}= 0.15	G_{31}= 1.52
Tensile Strength (MPa)	Compression Strength (MPa)*	Shear Strength (MPa)
S_{1T}= 373,133	S_{1C} = 366	S_{12}= 50
S_{2T}= 373,133	S_{2C} = 366	S_{23}= 35
S_{3T}= 50*	S_{3C} = 600	S_{31}= 35
Fibre Shear Strength (MPa) - S_{FS}= 300	Interlaminar Normal Stress: 27 MPa Interlaminar Shear Stress: 30 MPa	

3. Finite Element Model details

Quasi-static tests were modelled and simulated using the v15 ANSYS Workbench and AUTODYN explicit dynamics solver. Composite laminate plate of 6 mm thickness was modelled by bonding 10 plies of solid bodies (each 0.6 mm) with an interface between every two plies, defined by normal and shear stress failure criteria to simulate delamination (de-bonding of plies). Orthotropic elastic material model, including orthotropic strength values, were assigned to the composite material to simulate anisotropic nature of the material. Orthotropic post--failure feature is used with material stress failure criteria to detect the failure maps during the simulation. Details regarding these features can be found in the v15 ANSYS manual (ANSYS Help Viewer, 2013). As through thickness behavior is important, solid elements were used in the simulations rather than shell elements. The punch and fixture plates were modelled with steel material which is available in the software material library. Fixture plates and the punch were modelled as rigid bodies as they didn't exhibit any deformation in the tests. From the observations of the experiments, the parts of the laminate that is outside the boundary of the central hole is not affected from any damage mechanisms. Thus, in order to increase time efficiency of simulations, only the central part of the laminate is modelled for quasi-static simulations.

It is desirable to simulate an event with its real natural occurrence time. However, it is impractical to do in QSP simulation case without the necessary modifications in modelling because the time increments in an explicit dynamics analysis is at 1×10^{-10} s levels, which will lead to millions of simulation cycles for a real-time equivalent analysis. One of the ways to obtain reasonable results in a reasonable time period is to load the material with a maximum crosshead speed which doesn't exceed 0.1% of the wave speed of the material. With this method, inertial forces remain insignificant and do not affect results significantly and the first deformation mode of the structure in the QSP case doesn't change. The typical wave speed of GFRP material is around 3 km/s, and 0.1% of this value is equal to 3 m/s. In the present simulation 1 m/s crosshead speed is used.

The lack of available material property data necessitated the use of QSP in order to calibrate the required inputs for the software by comparing it to the physically tested case with the help of force-displacement graphs and damage progression patterns. In order to observe how the damage progresses in the material, QSP tests are performed with a stepwise approach. In this approach, composite laminates were loaded up to predefined displacement levels and then unloaded to be analyzed for the type and extent of damage. The number of steps can be determined by first fully penetrating a sample, and analyzing the force-displacement graph for any changes in the loading rate, which shows the influence of damage/failure. This way, specific damage types can be associated with displacement levels. The same analysis of damage progression can be tracked in a single successful simulation.

Since previous research ((Sun and Potti, 1996), (Gama and Gillespie, 2008)) showed that the deformation and damage behavior of composite laminates exhibit similarities between high velocity impact and quasi-static punch tests, successful simulations of QSP tests means that the material inputs can be used for high-velocity impact cases to see if a relation can be found between the two event. Most certainly the inertia of impactor would affect the material's response. This response can be obtained by incorporating strain rate change effects with the quasi-static FE material model. Although it will not be mentioned in this particular paper, it will be a part of the future study, thus, high velocity impact simulations will be mentioned here as preliminary information. High velocity simulations were also carried out with the same configuration and boundary conditions of QSP test cases for different impact velocities.

4. Results and discussion

In this section, focus will be given to both experimental and simulation findings for circular flat punch case.

4.1. Experimental results

Mines et al. reported that flat ended missiles have a greater dynamic enhancement factor, which is the ratio of dynamic perforation energy to static perforation energy (Mines et al., 1999). In short, circular flat tips can better reflect the maximum energy absorption potential of the composite material. However, in their work, this factor was considered for ratio of laminate thickness t to impactor diameter D, $0.5<t/D<2.5$. Thus, the same outcome cannot be expected in the present case in terms of absorbed energy values ratios because t/D ratio is 0.23, meaning that the laminates are thinner. Previous research on QSP tests were carried out for thick section composite laminates by other researchers. For the purpose of this research, the laminates were not thick because using thick laminates in a sandwich material (potentially preferred composite structure type for rail carbody shells) would not serve the purpose of light-weighting for a rail vehicle carbody shell. Nevertheless, it can be seen from the Fig. 2 that energy absorbed by laminates are higher for CF tip compared to H tip.

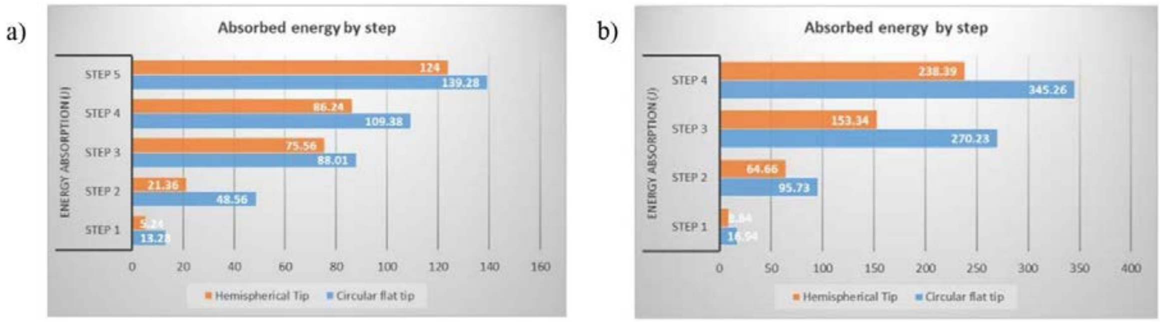

Fig. 2. Comparison of absorbed energy for CF and H punch tips a) SPR 1.2; and b) SPR 4.1.

As mentioned before, the damage progression in QSP and HVI cases were observed to be similar. Fig. 3 shows the comparison of the sectioned composite laminates after the step-wise QSP tests and the damage pattern of a typical HVI event. The sectioned laminates were dipped in ink to ease visual inspection and to see the extent of delamination. It can be seen from a) of Fig. 3 that after the contact phase (Phase I), which generates an intense compression force on the impact side, a stress wave propagates through the thickness of the laminate. The movement of the projectile results in a compressive shear failure and the formation of a plug (Phase II) of ruptured fibres and matrix material beneath the projectile. It continues to push the plug (Phase III), which results in the increased tensile stress and eventually tensile failure at the back face of the laminate (Phase IV). Fig. 3 b) shows the step-wise QSP test with GFRP for SPR1.2. It can be seen that the progression of damage is quite similar to the HVI case. Following the contact phase of the punch, minor delamination areas begin to progress through the thickness, then compression shear failure begins at Step 3 resulting in the formation of a plug front, accompanied by the delamination. Further moving of the punch leads to the tensile failure at the back face (Step 4), indicating the biggest load drop in the force-displacement graph (Fig. 4). Finally, Step 5 is showing the plug leaving the laminate and this last phase can be seen as the continuous load drop at Fig. 4.

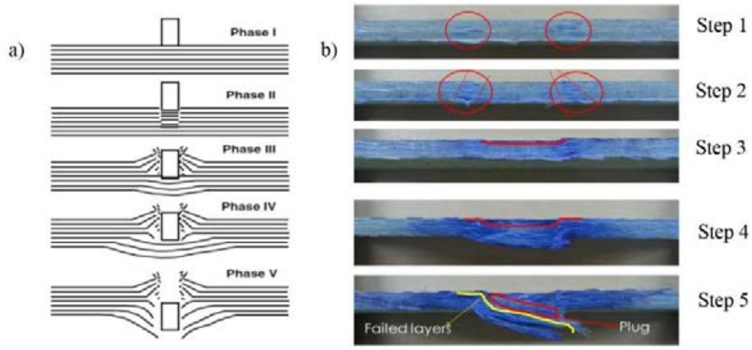

Fig. 3. Damage pattern of a) HVI; and b) QSP.

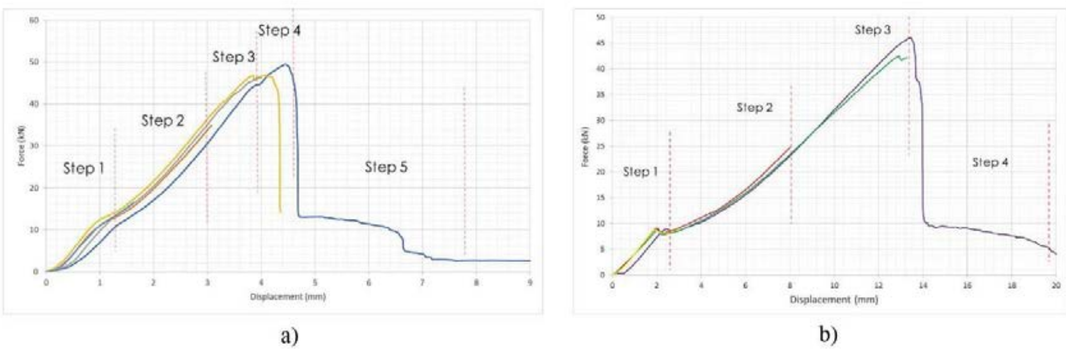

Fig. 4. Force-displacement graph for CF punch tip; a) SPR1.2; b) SPR4.1.

A similar damage sequence was obtained for SPR 4.1 with CF tip (Fig. 5), but this time with an increased contribution on energy absorption from delamination because of the bending of the laminate caused by the increased span length. Front and back side images of SPR4.1 case is given in Fig. 5 for a different perspective, again after being dipped in ink. Matrix cracks are increased in the front face after the first compression shear damage and the whitened area in contrast with the rest of the plate, indicates the delamination progress. Minor matrix and fibre damage can be seen at the back face caused by the edge of span hole.

4.2. FE Modelling results

QSP test model was created via the ANSYS Workbench platform and it is imported to AUTODYN for the solution. Due to the unavailable material data and the shortage of time, maximum force and displacement values for GFRP laminates was underestimated by the simulations as can be seen in Fig. 6. Despite this, the simulation was able to catch the overall response and the non-linear behavior of the laminates was quite similar to the experimental case. This was particularly so at the beginning of the simulation. From the non-linear part up to the 5 mm crosshead displacement shows excellent agreement with the experiment, and it also represents the softening behavior after the maximum load in good correlation. One of the reasons to partial disagreement might be the crosshead velocity. Although it is in the quasi-static limit range, there is still a possibility that the strain rates of the material is affected by it. However, the current model does not incorporate the strain rate change effects which will be carried out in the future. This underestimation also leads to the lower values of absorbed energies since its value depends on the area under the force-displacement curve. Fig. 5 shows the simulation results compared with the experimental case for front and back side of the laminates. The first failure was predicted as matrix cracks at inner plies at 3 mm punch displacement and the first compression shear failure was predicted at 5 mm, however this was more visible at 6 mm, whilst in the experimental case it was at 3 mm. However, the biggest load drops were due to the fibre tensile failure at the back face for both the simulation and the experiments, as shown with the purple and yellow contour colors.

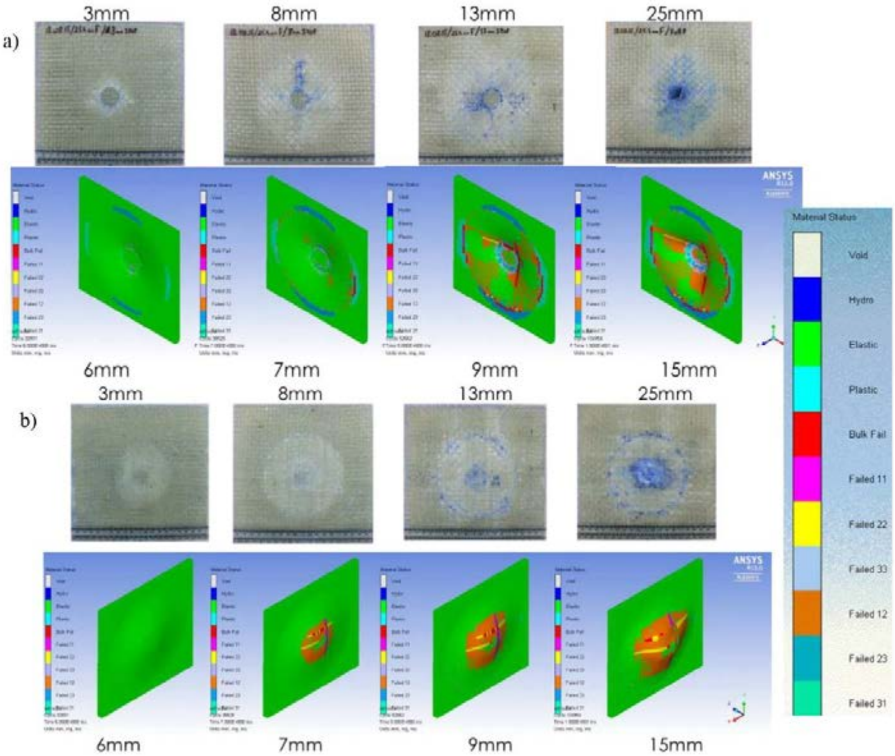

Fig. 5. Damage progression of laminates for SPR 4.1 with CF punch tip: a) impact face progression – experiment and simulation; b) back face progression – experiment and simulation.

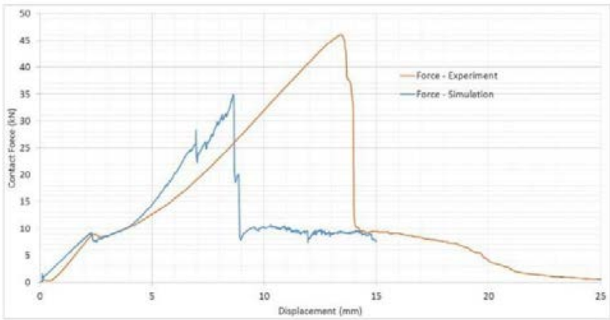

Fig. 6. Force-displacement graph for experiment and simulation (SPR4.1).

The material data and model used in the QSP simulations were used in HVI cases for four different velocities (40 m/s, 70 m/s, 100 m/s, 130 m/s) to obtain the response of laminates with the same boundary conditions. The velocity levels were chosen according to the required missile speed levels in GM/RT-2100, based on rail vehicle operating speeds plus 160 km/h (144, 252, 360, 468 km/h, respectively). The projectile was in the same diameter of the QSP tests and had a length of 20 mm, weighting 0.08 kg. Fig. 7 shows the kinetic energy and total energy change for the projectile and GFRP, respectively. For 40 m/s and 70 m/s cases, the projectile rebounded from the laminate, causing local damage. For 100 m/s and 130 m/s velocities, it penetrated the laminates, its kinetic energy absorbed by various damage mechanisms of the laminate, and left the plate with a residual velocity. In a full penetration case, the kinetic energy of the projectile is mostly absorbed by the laminate via different damage mechanisms, and a negligible amount is lost in the fixture and also by the friction between sample and projectile. In Fig. 7, the kinetic energy change of the projectile is calculated as 318J, and the total energy change of GFRP is calculated as 281J. It can be seen from Fig. 2 that the energy absorbed by the laminate was 345 J for the experimental SPR4.1 case. In spite of the underestimated force values in the simulation of the static case, the energy absorbed by static experiment and dynamic simulation is close to each other. This information, combined with the failure maps in Fig. 8 provides a positive connection between the two cases. In Fig. 8, the failure maps are shown at the moment of the biggest load drop in QSP and HVI cases. It was observed that the cause for the load drop is fiber tensile failure at the back face (yellow and purple contour for fibre directions), while the front face failed by compressive shear damage during the earlier phase (blue-orange-light pink contour color indicating shear along with red as bulk failure which denotes zero tensile stress).

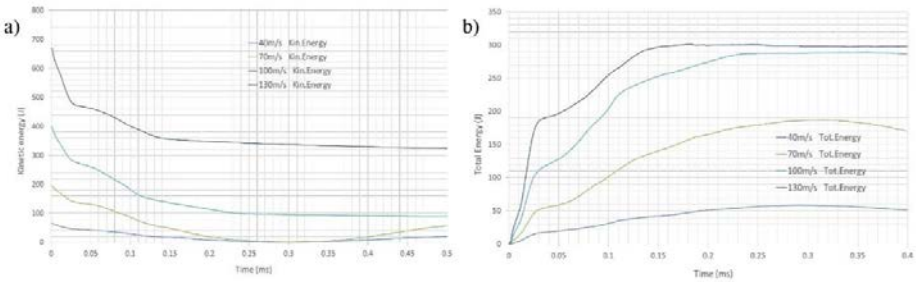

Fig. 7. HVI results for GFRP laminates; a) Kinetic energy change of projectile; b) Total energy change of laminate.

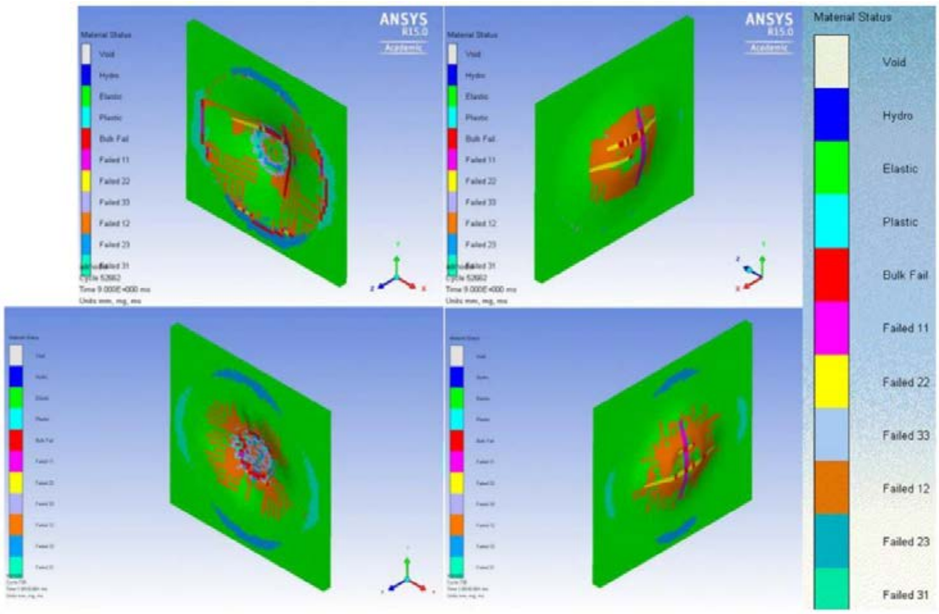

Fig. 8. QSP and HVI front and back face failure map comparison - top row QSP, bottom row HVI.

5. Conclusions

This paper puts forward an alternative approach to impact damage analysis of composite materials and in particular for railway rolling stock. The expected outcomes, in terms of numerical correlation and a better in-depth representative mechanism/explanation, have been hindered by the timing of the current study. However it is anticipated that the overall approach and basic understanding will continue to feed into and develop future work.

This research presented the similarities between the static experimental and typical dynamic event and the numerical work between the static and dynamic case. Further calibration on both the material data and/or modelling is required, however it has been demonstrated that the static and dynamic behavior of E-glass/polyester GFRP can be simulated to a reasonable degree with reasonable results in order to analyze failure behavior and energy absorption.

This outcome could lead one to choose a static experiment over high-speed testing in order to get an understanding about the material response. This would precede simulating the same case in order to predict and anticipate what might happen in a real life high velocity impact situation. It is anticipated that future research would aim to carry out the same concept for sandwich materials thereby benefitting the railway industry where the trend towards using composite materials is increasing.

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