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EXPERIMENTAL VERIFICATION OF SIMULATION MODEL OF IMPACT RESPONSE TESTS FOR UNSATURATED POLYESTER/GF AND PP/GF COMPOSITES

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Abstract

In this paper validation of experimental and numerical results of low-velocity composite plate impact tests have been carried out. Good validation results allow designing large scale composite structures required by specific industries. Experimental impact tests were performed using drop-tower Instron 9250HV determining impact force and energy absorption of materials. In addition, quasi-static testing equipment Zwick Z100 has been used to determine material mechanical properties to ensure good input data for numerical predictions. Numerical model has been created with the finite element commercial code LS-DYNA to simulate impact response of unsaturated polyester/glass fibre and polypropylene/glass fibre (PP/GF) composite laminate. Finally ultrasonic imaging system USPC 3010 has been used to identify the delamination growth and rupture regions in the specimens.

Results of experimental impact tests indicate that PP/GF composites are capable to absorb more energy and better resist impact compared to polyester/GF composite. Response of both composite laminate types were simulated in LS-DYNA with good agreement, with the exception of deformation regions that are larger than observed in experimental specimens with non-destructive ultrasonic imagining system.

Key words: plate impact, LS-DYNA, PP/glass fibre, impact simulation, composite simulation

1. INTRODUCTION

The ability to design highly specific mechanical properties in composite laminates is leading to increased use in a number of different engineering fields such as aircraft, railroad, automotive and marine industry. Drawback of polymer composites compared to metals is more brittle response to impact followed by fibre fracture, matrix cracking, fibre-matrix debonding and delamination. Also laminates poorly resist and dissipate impact energy in transverse direction, thus 3 D textiles and hybrid laminates are introduced. Hybrid composites made of carbon/glass fibre fabrics are more in detailed studied by Wang et al. (2010).

Impact properties can also be enhanced by replacing more common glass fibre fabric composites based on thermo set matrix with thermoplastic matrix. The advantages of thermoplastic matrix are shorter processing time, possibility to recycle, higher toughness and impact absorption capability, also in the case of PP lower density. Additionally, an interest arises about the capability of thermoplastic composites being repaired and to gain back some strength properties lost after having been subjected to low velocity impact due to thermoplastic remelting property, this phenomenon is described by Reyes and Sharma (2010).

Impact response of composite laminate plates is frequently studied by impact tests. Plate impact tests

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mostly are carried out to study crashworthiness, residual properties and high velocity impact response of materials. Residual properties after low velocity are widely researched and still are relevant. Wang et al. (2010) have determined changes of carbon/epoxy laminates residual tensile properties after different low velocity impact loads and divided residual strength degradation into three stages. Davies and Olsson (2004) describe the velocity rate and impact time influence to composite material response.

Furthermore, plate impact tests are frequently combined with numerical simulation because the possibility to use results of simulation for large scale objects reduce the design costs associated with prototype manufacturing. Wang et al. (2010) achieved very good agreement between experimental and simulation results obtained using ABAQUS/Explicit. Karakuzu et al. (2010) implemented 3DIMPACT to simulate epoxy/glass fibre laminate composites, some simulation models in LS-DYNA are given by Brown et al. (1998) and Heimb et al. (2008). General purpose finite element code LS-DYNA is one of the most frequently used commercial codes in crash test simulations by car industry, as well as in aerospace, metal forming, material processing, sport, biomedical and other industries. Schweizerhof et al. (1998) and Matzenmiller et al. (1995) give insight in capability of LS-DYNA to model composite laminates.

Moreover, visual inspections of impacted materials with methods as microscopy, C-scan ultrasonic methods, and IR thermographs are often used to evaluate damage area, delamination, dominating fracture type etc. Sevkat et al. (2009) used the ultrasonic C-scans method to evaluate damaged areas of glass fibre and toughened epoxy composite after impact.

Impact properties of composite laminates are widely studied, but still there is increasing demand from industry to efficiently replace metal constructions with polymer composites. The aim of this work is to evaluate polypropylene matrix influence to impact response of composite laminates and simulation capabilities of LS-DYNA using simple composite material models. Experimental and numerical studies of two kinds of composite materials are presented. Additionally mechanical properties have been determined as difference between specification and experimental data was observed due to composite processing. Moreover, non-destructive ultrasonic scanning method was used to evaluate rupture and delamination area of composites.

2. EXPERIMENTAL TESTS

2.1. Specimen manufacturing

In order to study polyester and glass fibre (GF) composites orthophthalic polyester POLYLITE 440-M888 resin and glass fibre fabric AERO having a weight of 80 g/m² has been selected. POLYLITE was mixed with 1.5% Norpol Peroxide to initiate free radical polymerization cross-bonding polyester linear molecules with styrene. Composite consisting of fourteen glass fabric layers with the total thickness 1.3 mm has been made by hand lay-up processing method at the room temperature.

The second composite specimen was made out of thermoplastic matrix – polypropylene. Such composite consisting of commingled PP and glass fibre fabrics are available with the trade name Twintex. Composite fabrics with 60% of glass fibres and balanced structure were processed with vacuum moulding at 200°C for 20 minutes having symmetric lay-up stacking made of 1, 2 and 3 layers with total thickness ranging from 0.65 to 1.50 mm

2.2. Determination of mechanical properties of composite laminates

Mechanical properties of composite were tested with quasi-static testing equipment Zwick Z100 employing 100kN load cell with test data acquisition rate of 10 Hz. In order to determine tensile and shear moduli and Poisson ratio (according to ASTM standards D3039 and D3518) HBM strain gauges 6/350E LY4/S-3 with resistance 350Ω, gauge factor 2.06 and transverse sensitivity 0.4% were used. The dimensions of specimens were 250 x 25 mm and gauge length 100 mm. Applied testing speed was 2 mm/min for tensile and 5mm/min for shear properties determination. Obtained average mechanical properties of composite specimens are summarized in table 1.

Table 1. *Mechanical properties of composite material.*

Property, unit	Polyest./GF	PP/GF 1:1
$\sigma_{tensile}$ (90°), MPa	130 ± 5	270 ± 5
E (90°), GPa	11.6 ± 0.5	10.5 ± 0.5
In plane shear strength, MPa	38 ± 1	30 ± 1
In plane shear modulus, GPa	3 ± 0.15	0.86 ± 0.05
$\sigma_{tensile}$ (0°), MPa	164 ± 5	270 ± 5
E, GPa (0°)	13.7 ± 0.5	10.5 ± 0.5
Poisson's ratio	0.15 ± 0.01	0.10 ± 0.01

2.3. Impact testing

The low velocity impact tests were performed by drop tower INSTRON Dynatup 9250HV. The equipment allows varying drop weight and height up to 20 m and impact speed up to 20 m/s. During test impact machine was equipped with a hemispherical 15.6 kN indentor with diameter of 10 mm. Specimens with dimensions 100 x 100 mm were fixed in pneumatic clamping system with inner ring diameter 76.2 mm. Impact velocity was set to 2.035 m/s to provide resultant impact energy of 14 J.

2.4. Ultrasonic inspection of deformed composite laminates

The non-destructive ultrasonic imaging (NDUI) system USPC 3010 was used to analyze impacted region and delamination growth of specimens. The system consisted of a computer-controlled ultrasonic flaw detector USPC 3010 Industrial, an immersion ultrasonic probe of 5 MHz, a glass water tank, and a stepper motor-controlled XYZ-manipulator.

3. NUMERICAL SIMULATION

3.1. Building of material model

Impact specimens were modelled using shell elements with equal distribution of integration points corresponding to each layer, 14 integration points for unsaturated polyester/GF and 1 to 3 to PP/GF composite, respectively. Impact energy, velocity and indentor diameter, sample constraints were set accordingly to experimental test. As shown in figure 1 simulation include initial velocity direction and node rotational and translational constraints in 38 mm radius from centre. Indentor is modelled as rigid ball using material model MAT22_Rigid. Similar modelling approach has been described by Karakuzu et al. (2010).

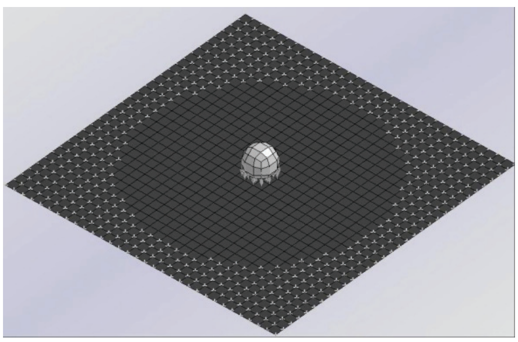

Fig. 1. *Simulation model in LS-DYNA.*

3.2. Applied material models

A wide range of composite material models exist in LS-DYNA. MAT54 and MAT58 models were chosen for this study. MAT 54 was used to simulate unsaturated polyester/GF composite impact response. This composite material model based on the Chang-Chang failure criterion allows us to describe anisotropic, linear elastic behaviour of the material. This criterion defines material failure or elastic response of fibre and matrix in the tensile or compressive mode depending on applied load. Element is deleted once the failure criterion is satisfied.

Together with mechanical material properties from table 1 used in MAT 54, strain limiting parameters given in table 2 were used to enhance agreement between simulation and experimental results. Strain limiting parameters (DFAIL) allows transition from linear-brittle to elasto-plastic behaviour of material in fibre tension (T), fibre compression (C), in matrix (M) and shear (S) deformation. More detailed information about laminated composite model is given by Hallquist (2006).

Table 2. *Parameters in model MAT54.*

	Polyest./GF	PP/GF 1:1
DFAIL(T)	0.04	0.15
DFAIL(C)	-0.035	-0.10
DFAIL(M)	0.20	0.30
DFAIL(S)	0.13	0.15

Material model MAT54, however, did not show good agreement between PP/GF composite experimental and numerical results. Therefore the material model MAT58 based on the Hashin failure criteria was employed. A more detailed description of the model MAT58 is given by Schweizerhof et al. (1998) and Hallquist (2006). Depending on application in MAT 58 three types of surface failure can be chosen, which significantly change simulation results. The best agreement with experimental results was achieved when failure surface (FS) type was set to -1. It describes uncoupled failure of the composite, it means, all failure criteria as tension and compression for both the fibre and transverse direction, also shear deformation are taken to be independent for each other. This failure surface type allows predicting of non-linearity in the material response. A more typical elasto-plastic behaviour can be achieved using stress limiting factor SLIM(X). More information regarding to MAT58 can be found in the theory manual of LS-DYNA written by Hallquist (2006). Parameters used in MAT58 are summarized in table 3. TAU1 and GAMMA1 indicate the beginning of second linear region in shear stress-strain curve, therefore ERODS characterizes effective deformation in percents, E11T/22T – tension deformation in longitudinal and transverse direction and GMS shear deformation at shear strength.

Table 3. *Parameters used in MAT58.*

TAU1	0.02	E11T	0.035
GAMMA1	0.02	E22T	0.035
SLIM(T1)	1	GMS	0.07
ERODS	1.70		

4. RESULTS AND DISCUSION

Experimental impact results such as contact force and energy absorption are compared for unsaturated polyester/GF and PP/GF specimens in figure 2. Based on the physical tests the polyester/GF composite reaches almost three times lower impact force and two times lower absorbed energy than the PP/GF composite of the similar thickness.

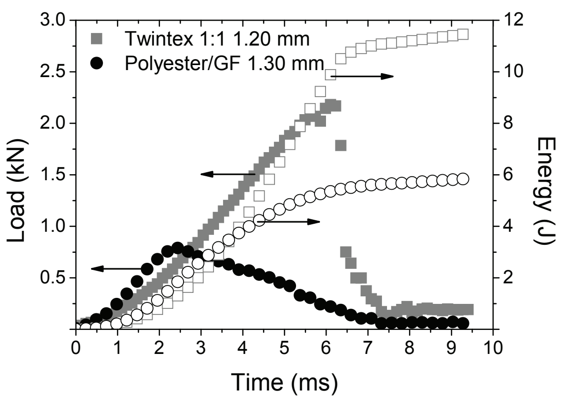

Fig. 2. *Impact load and energy of balanced PP/GF and unsaturated polyester/GF.*

The impact force below its maximum is governed by the bending resistance of composite materials during impact. The contact force curve of polyester/GF composite is steeper because of higher Young modulus, while PP/GF has longer contact with indentor due to higher deformation capability. The attention should be drawn to impact force changes after reaching maximum in the case of unsaturated polyester/GF composites. Moreover smooth decrease of impact force has been observed, while PP/GF composite show quite sudden decrease. This can be explained by the delamination evolution in the unsaturated polyester/GF composites, while only a very small delamination was observed in PP/GF composites with NDUI system. Similar testing praxis has been shown by Sayer et al. (2010) for impact tests.

An absorbed energy in perforated specimens can be determined as shown in figure 3, where the impact force curve is aligned with its corresponding energy absorption curve. The perforated energy was acquired at the penetration point, where the load–time curve has sharp decrease. The energy–time curve continues to ascend due to the friction between the edges of the perforation hole against the lateral surface of the indenter.

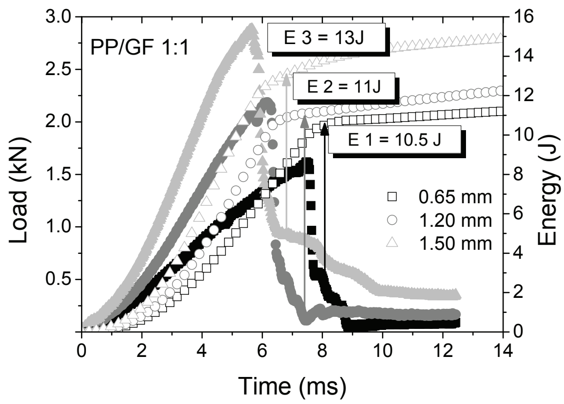

Fig. 3. *Comparison of impact load between different thickness plates.*

PP/GF composite contact load and absorbed energy variations are compared for the samples with different thickness in figure 3. As it was expected, impact load and energy increases with the thickness of material. However increase of impact load and energy with increase of thickness does not show any linear correlation.

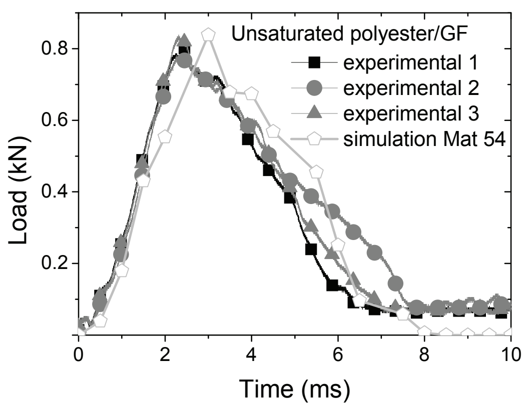

Fig. 4. *Unsaturated polyester/GF simulation results compared to experimental.*

Similarly, LS-DYNA simulation of the plate impact has given such results as absorbed energy, impact load and deflection. Unsaturated polyester/GF composite simulation results with quite good agreement to experimental one are shown in figure 4. The same material model MAT54 was applied to simulate PP/GF composite, but with less satisfactory results as shown in figure 5. Impact force curve predicted by model 54 is steeper than experimental curve. Better correlation between LS-DYNA simulation and experimental results were achieved implementing material model 58.

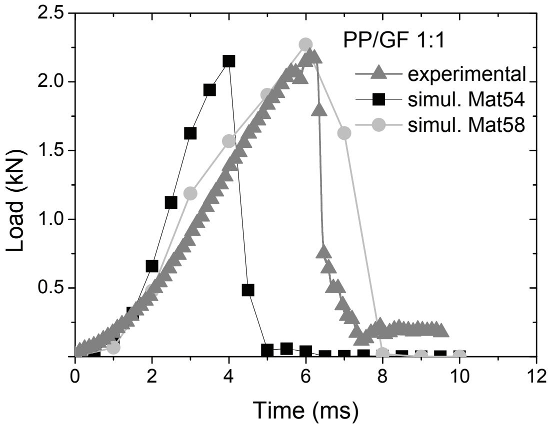

Fig. 5. Simulation of PP/GF impact response with MAT54 and MAT58.

In addition material model 58 allows predicting with good agreement ascending part of impact load curve, while less successful is the sudden drop of impact force after reaching the maximum. The numerical results are within the range of dissipated experimental results in particular in the descending area as it is shown in figure 6.

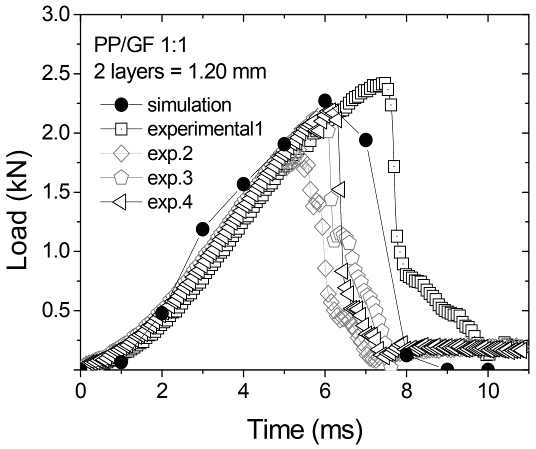

Fig. 6. Impact force vs. time. Experimental results of PP/GF composite.

Furthermore, in the case of PP/GF composite all samples with different thicknesses were simulated using the same parameters and mechanical properties to evaluate, how robust is the simulation achieved beforehand. Understanding of the robustness is important for predicting large scale object impact where experimental tests would not be available. The robustness study results are summarized in figures 7 and 8. The highest disagreement was in the case of one layer plate what is more pronounced because of disagreement in ascending part of the load curve, while three layer plate curve similarly to two layer specimens is more expanded than it is experimentally determined.

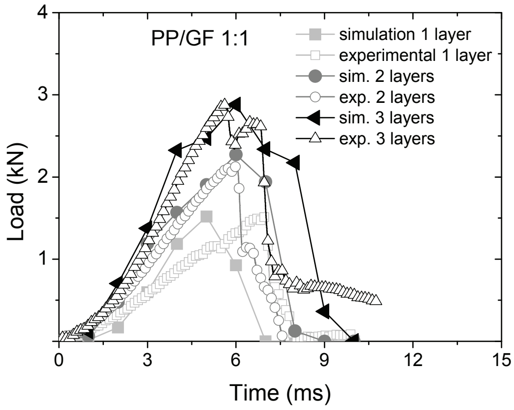

Fig. 7. Simulation of plates with different thicknesses.

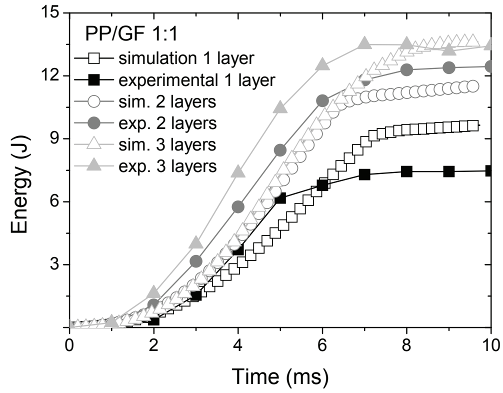

Fig. 8. Predicted and experimentally observed absorption energy of PP/GF.

It is also important to evaluate the deformation character of experimentally tested and simulated specimens. First of all it was interesting to compare different manner of deformation due to impact of polyester/GF and PP/GF composite what is given in figure 9. PP/GF composite laminates show highly localized deformation and perforated region with good agreement to indentor form, while polyester/GF specimens were perforated by indentor showing larger rupture diameter than indentor tip and also quite large delamination region.

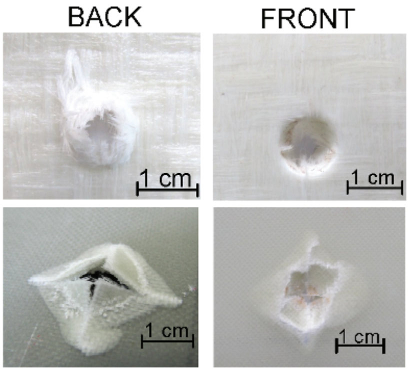

Fig. 9. Visually compared impacted PP/GF and polyester/GF composites.

Shyr (2003) observed that the structure of the reinforced polyester/GF material strongly affects the delamination pattern and area surrounding it. In woven fabric laminates with stacking sequence $0^o/90^o$ delamination has a rhombus shape and it was aligned in warp and weft directions, thus is more pronounced in fibre direction and has lower extent in 45^o direction. Similar delamination shape of unsaturated polyester/GF was observed in this study. Quite different it is in the case of PP/GF composite were delamination is very small and has circular shape, what can be better observed using ultrasonic scanning as it is shown in figure 10.

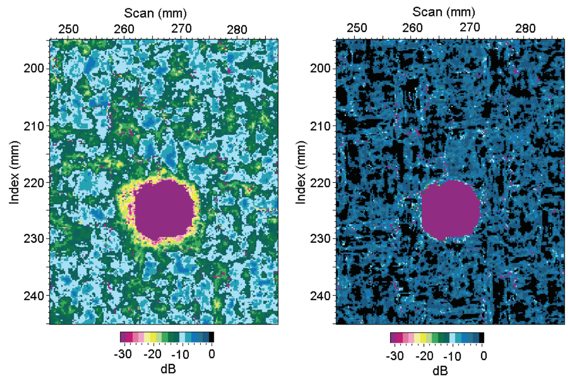

Fig. 10. NDUI results of PP/GF 3 layers composite in plane direction.

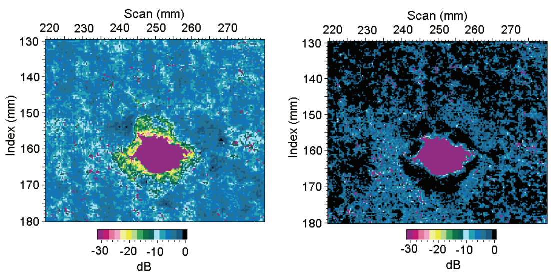

Fig. 11. NDUI results of polyester/GF composite in plane direction.

In the figure 10 and 11 the ultrasonic scanning results of PP/GF and unsaturated polyester/GF composite are shown both from front and back surface. Scanned area in figures 11 and 12 is 30 x 40 mm for PP/GF composite and 60 x 50 mm for unsaturated polyester/GF composite. Delamination in the case of PP/GF is more visible from bottom surface and its length is about 1-2 mm, while in the unsaturated polyester/GF composite in some parts delamination exceeds 10 mm. For unsaturated polyester/GF composite delamination can be well observed from both front and bottom surfaces.

In addition, ultrasonic scanning trough thickness can be done as it is shown in figure 12 where scanning length is equal to specimens' width. Figure 12a corresponds to unsaturated polyester/GF composite with clearly evident delamination region. Whereas 12b shows scanning results of PP/GF trough thickness and no delamination can be recognized. In figure 12b it seems that echo from bottom surface is too weak to trace significant differences, thus delamination cannot be observed.

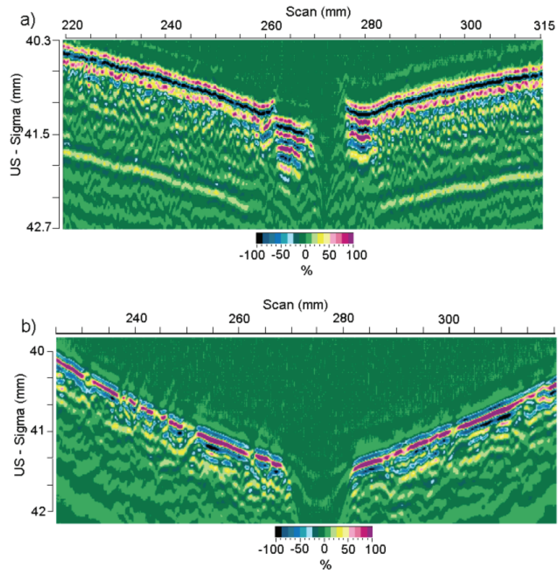

Fig. 12. NDUI results in thickness direction.

In the figure 9 and also in the ultrasonic scanning results it can be observed that rupture area of polyester/GF composite due to impact has a tendency to extend because of matrix cracking. On the contrary, PP/GF samples show highly circular deformation coincidence with indentor cross-section, thus showing more explicit plastic deformation. It should be noted that the cracks around the perforated region were not observed. This is also affirmed by Reyes and Sharma (2010) study of PP/GF composites with SEM.

The data determined visually are compared with calculation results in figure 13, where simulation results for MAT 58 correspond to PP/GF and those for MAT54 to unsaturated polyester/GF composite. In both cases LS-DYNA shows higher degree of deformation in x or y axis. This means that good agreement has not been achieved.

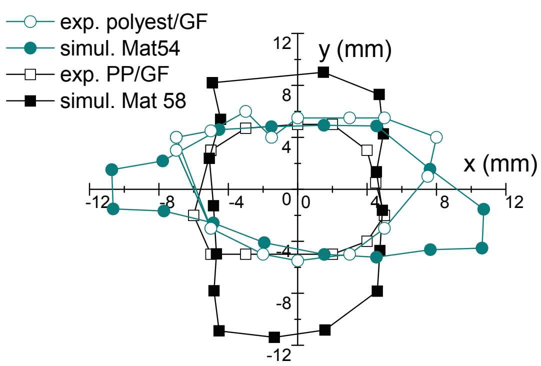

Fig. 13. *NDUI results compared with simulation.*

5. CONCLUSIONS

Experimentally it was observed that PP/GF fibre composites show much better energy absorption capability, higher impact load and plastic response to the impact and very small delamination.

Simulation results show that MAT 54 in LS-DYNA is more suitable to predict unsaturated polyester/GF and MAT58 PP/GF composite response. The parameters determined for material model MAT58 were applied to predict response of plates with different thicknesses. Results are quite contradictory as decreasing the thickness the agreement gets poor, while increasing the thickness numerical results are in the range of disperse experimental results. Also it was concluded that LS-DYNA predicts larger deformation regions than it was observed with ultrasonic imagining system.

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WERYFIKACJA MODELU NUMERYCZNEGO PRÓBY UDARNOŚCI DLA MATERIAŁÓW KOMPOZYTOWYCH POLIESTER/SZKŁO ORAZ POLIPROPYLEN/SZKŁO

Streszczenie

Tematem niniejszej pracy jest doświadczalna weryfikacja modelu numerycznego prób udarności przeprowadzanych przy małych prędkościach dla materiałów kompozytowych typu laminat poliester/włókno szklane i polipropylen/ włókno szklane. W tym celu przeprowadzono próby udarności na maszynie Instron 9250HV i wyznaczono siłę oraz energię absorbowaną przez badany materiał. Ponadto dla oszacowania własności materiału istotnych dla symulacji numerycznej procesu przeprowadzono quasi-statyczne próby odkształcania na urządzeniu Zwick Z100. Do symulacji próby udarności wykorzystano komercyjny program oparty na metodzie elementów skończonych LS-DYNA. Dla wyznaczenia stref rozwarstwień lub pęknięć w badanych laminatach wykorzystano ultrasonograficzny system obrazowania USPC 3010.

Wyniki prowadzonych badań laboratoryjnych potwierdziły, że materiały kompozytowe typu poliester/szkło są wstanie zaabsorbować więcej energii niż kompozyty na bazie poliester/włókno szklane. Wyniki doświadczalne porównano z wynikami symulacji numerycznych, otrzymując zadowalającą zgodność, z wyjątkiem wielkości strefy odkształcenia, która była nieznacznie większa w symulacji numerycznej niż to wynika z pomiarów.

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