STRAIN RATE EFFECTS ON NOMEXTM HONEYCOMB CORE INVOLVED IN LOW VELOCITY IMPACTS ON SANDWICH PANELS

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Abstract
Sandwich panels nowadays are used in many industrial fields, in particular where needs of lightness and energy absorption capability are required. Thus, in order to increase their exploitation it is crucial a wide knowledge of their mechanical behaviour also in severe loading conditions. The capability to develop robust and reliable finite element models able to numerically reproduce the mechanical behaviour of sandwich panel in critical situations, such as impacts, is an actual key task. Therefore, focusing on material model calibration, a complete numerical\experimental approach will be illustrated in order to evaluate strain rate behaviour of Nomex^{tm} honeycomb structures adopted as sandwich panels' core. Not only strain rate effect has been evaluated but also other significative parameters such as specimen dimensions and skin thickness. Experimental stabilized upsetting tests at various speeds and with different panels configurations have been carried out. All the experimental data have been studied through a statistical approach (ANOVA) in order to quantify the effect of various parameters on the load-displacement curve. Moreover free falling tests on sandwich panels with Nomextm honeycomb core and Al2024 aluminium alloy skin have been also done. Experimental results have been then compared with numerical results: a micro mechanical finite element model of the sandwich panels. The FE model is able to reproduce with very good similarity damage due to impacts in terms of damage profile taking benefit of the strain rate calibration of the core. This work represents the end of a wider research involving the complete mechanical characterization of sandwich panel with Nomextm honeycomb core and Al2024 aluminium alloy skins in order to build a high accurate FE model able to reproduce low velocity impacts.

1 Introduction

1.1 Tested sandwich panels

Structure like sandwich panels can suffer a significative reduction of their structural integrity when they are hit by low velocity impacts. Their construction with very thin skins and a lightweight core is very sensible to normal to plane impact; however the Honeycomb core (H.C.) plays a key role in absorbing impact energy in sandwich structures. Concerning this topic, it is important to verify the behavior of H.C. under impact condition, thus in presence of large deformation and strain rate.

In present research the H.C. is made by NOMEXtm. The trade name is A10, manufactured by Hexcel Composite. It consists of Dupont's NomexTM aramid-fibre paper, dipped in a heat-resistant phenolic resin to achieve the final volumic mass. Its characteristics are high strength

and toughness in a small cell size with low volumic mass. Generally a thermosetting adhesive is used to bond these sheets at the nodes, and, after expanding to the hexagonal configuration, the block is dipped in phenolic resin. In particular the tested H.C. has a trade code of A10-32-5. According to the datasheet of the manufacturer [1], the H.C. code name refers to its geometrical and mechanical characteristics. These attributes are expressed using the designation and nomenclature described in Tab.1. The metallic skins of panels are made by a Al2024-T3 aluminum alloy. The core is linked to upper and lower metallic plates using a modified epoxy film adhesive Redux^{TM} 312.
Two different panels configuration will be investigated with the aim to verify material mechanical behaviour focusing on properties aimed to simulate impact event. The differences between Type 1 and 2 are only geometrical: the overall thickness remains the same for both configuration but thickness of skins and core change. In Tab.2 data about the tested panel are summarized.

CODE: A10-32-5	**MEANING**
A10	designates honeycomb type
5	cell size [mm]
32 [Kg/m^3]	nominal volumic mass

Tab.1. Honeycomb designation and nomenclature

Panel	**Type 1**	**Type 2**
Honeycomb: A10-32-5		
Total thickness [mm]	22	22
Higher skin thickness [mm]	1	1.5
Lower skin thickness [mm]	1	1.5
Core thickness [mm]	20	19
Skin material	Al2024-T3	Al2024-T3

Tab.2. Main characteristics of the tested panels

1.2 Flatwise compression test

One of the objectives of the paper is to verify the effect of some parameters (including strain rate) on the behaviour of Nomex^{TM} H.C. In order to reach this goal flatwise compression tests have been carried out. It has been demonstrated in [2] that using out of plane compression test is possible to evaluate various important parameters regarding the behaviour of Nomex^{tm} H.C.. Experimental tests have been made starting from the normative approach [3]. This standard describe only quasi static test thus some variations have been made in present research. In order to evaluate the strain rate effect flatwise compression tests have been made using different crosshead velocity. Tests have been performed with a MTS Alliance RT/150 testing machine with a maximum load of 100 KN, and a maximum stroke of 1100 mm. Force has been introduced to the specimen using one fixed flat plate and one spherical seat, for the self-alignment to avoid the application of an eccentric force. The displacement has been acquired directly from the machine crosshead. It’s important to highlight that the moving compression plate of the machine wasn’t in contact with the upper skin of the panel at the beginning of the test. Using this approach it is possible to assess that the velocity of the crosshead is exactly the desired value when it starts to compress the panel. Indeed crosshead requires a certain amount of time in order to accelerate up to the desired velocity. Five different crosshead velocities have been evaluated: quasi static, 100, 300, 500, 700 mm/min. With this range of velocity the higher strain rate is about 30 s^{-1}. All the upsetting tests have been done using the complete panel specimen (H.C. and skins), this kind of test are also called “stabilized”. As already remarked in Tab.2, two different kind of panels having different thickness ratio between core and skin (but the same global thickness) have been evaluated. Moreover two different plane dimensions (50x50mm and 100x100mm) have been tested.

2 Results

2.1 Experimental compressive load-displacement curve

Before describing experimental results it is necessary to describe the common behavior of H.C. in compression. This aspect is important because it clarifies the most important parameters that can be inferred from the experimental curve. The first stage of the curve has been largely described in the literature [4]. In this region the behavior is elastic (thus reversible). The load increases in an almost elastic way, until a critical load is reached. After the peak load is achieved there is sharp drop of the load. This point is characterized by an extensive macroscopic buckling of H.C.. Starting from this point H.C. walls begin to fold. The folding continues in the curve region so called "plateau region". In this zone, stress levels remain almost constant. A mixture of a mainly global, but also a local collapse appears, which was also been observed in [5]. This is most likely caused by fractures, which develop under compression and bending inside the H.C. [6]. The amount of folding increases with the displacements up to reach a final point called "densification". From this point it is impossible for the H.C. to generate further folds because skins are too near. The densification point is characterized by a very significative increment of the load. The parameters on which it has been evaluated the effect of velocity, dimensions and type of panels (table 2) are:

- Load peak. It is the maximum load obtained at the end of the first linear zone
- Absorbed energy. This energy has been evaluated as the area under the load-displacement curve for a displacement between 2.5-8mm. The choice of this displacement range is due to the attempt to evaluate only the energy adsorbed in the plateau region.
- Plateau load. It has been evaluated dividing the absorbed energy (the integral of the force for the displacement) for 5.5mm that is the displacement range over the energy has been calculated. Using this approach it is possible to have a unique average value for the plateau load nevertheless in this region load suffers anyway slight oscillations.
- Slope of the first linear (elastic) region. It has been evaluated between the load of 4 and 9KN in order to have comparable values among the various tests.

Basically energy and plateau load have been obtained from the same data thus effect of parameters on these two quantities are exactly the same. They both have been reported due they are of interest from engineering point of view.
The nomenclature adopted to describe each experimental curve in the following figures can be found in Tab.3

Thk 1-1.5	**Big - small**	**#**
It refers to the panel type (Type 1 or 2). Thk1 means that the skin thickness is 1 mm thus the H.C. has a thickness of 20 mm (Type1). Panel Type2 instead has name thk1.5 because it has skins thickness of 1.5 mm and H.C. core thickness of 19 mm	It refers to the plane dimensions of the specimen • Big=100x100 mm • Small=50x50 mm	It refers to the test number

Tab.3. Nomenclature adopted to describe each experimental test

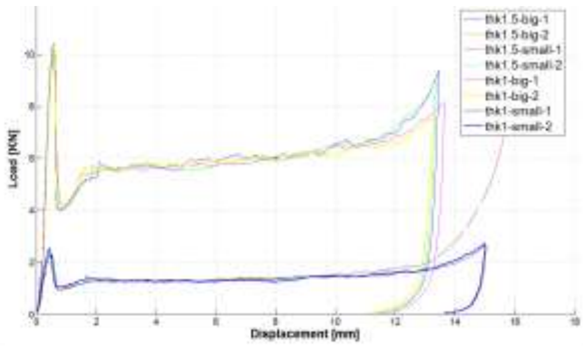

Fig.1. Experimental load-displacement curve for the quasi static flatwise compressive test

2.2 Effects of various parameters on the experimental load-displacement curve

In this section will be discussed the effect on the quantities described in previous paragraph (paragraph 2.1) of some significative parameters. These parameters can be inferred from Tab.3 but it is better to provide a brief clarification. Two different typology of panel on the base of the relative thickness of skin and core (Type1=thk1, Type2=thk1.5) and also two different plane dimension (big=100x100mm, small=50x50mm) of the specimens have been considered. In order to make comparable the results obtained for the small and big specimen in terms of load, it has been necessary to scale the results of the small ones. This is possible multiply for a factor of 4 the load data acquired for small specimens. This approach is possible due to the cellular structure of H.C. [2].

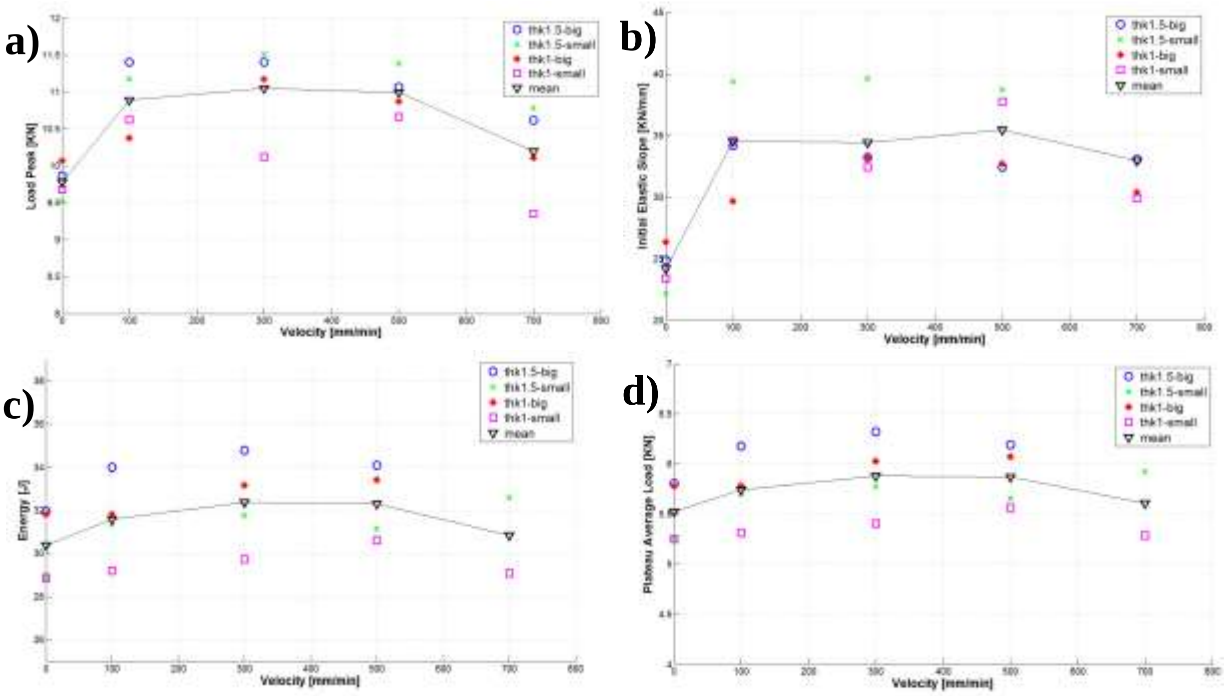

Fig.2. Effects of velocity on experimental load-displacement curve: a) Load peak b) Initial elastic slope c) Adsorbed energy d) Plateau average load

In Fig.2 it is possible to evaluate the effect of the velocity on the most important parameters that can be inferred from experimental load-displacement curve. Looking at the effect of velocity some interesting conclusions arise. The first important aspects is that velocity has always a nonlinear effect on each evaluated parameter. For what concerns the maximum peak load velocity causes a increment up to about 15% of the load. The trend shows a maximum for a velocity of 300 mm/min. For higher velocity the load decreases. This behavior appears different from the results found in [9]. In that paper using a drop weight tower it has been possible to evaluate the behavior of low density hexagonal NOMEX honeycomb for strain rate from 50 to 300 s^{-1}. Author found out that increasing strain rate lead to an increase of the plateau in the stress-strain curve of H.C. of about 10-30% depending on material directions. For the adsorbed energy (and also for the average load that is strictly connected with it) the effect of velocity is not so significative and it is about 5-6%. Finally the effect of velocity on the initial elastic slope is the most complex aspect to evaluate. There is a significative differences between the quasi static test and the others with higher velocity. Besides it is difficult to define an unique trend. In several cases the behavior show a dependence on specimen size, Figure 4a)

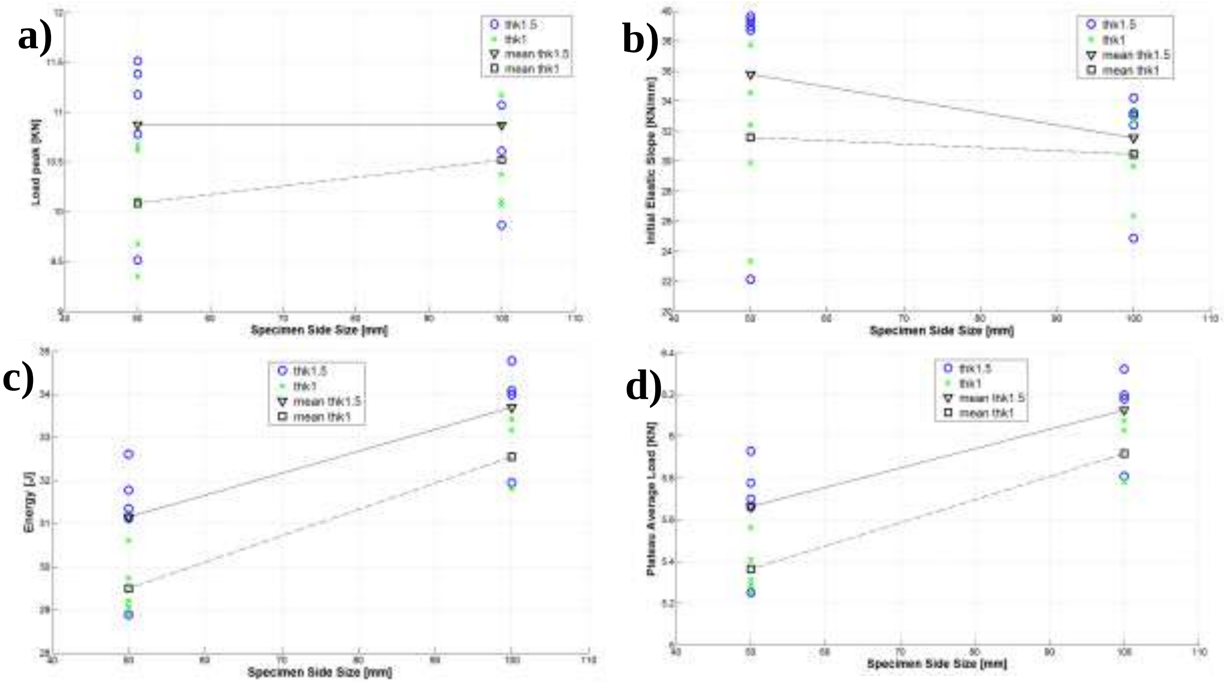

Fig.3. Effects of planar specimen size on experimental load-displacement curve: a) Load peak b) Initial elastic slope c) Adsorbed energy d) Plateau average load

For what concerns the effect of specimen size, Fig.3, it is possible to see an increment of the peak load of about of 5% for specimen with a skin thickness of 1mm (increasing the size of the panes). Instead for specimen with 1.5mm skins, specimen dimensions don't have significative effects. Also the average plateau load and the adsorbed energy have the same trend but in this case the increment is only about 7%. Finally about the initial elastic slope, increasing the size of the panes there is almost no dependence for 1mm thickness specimen instead for the specimen with a thickness of 1.5mm, the slope decreases of about 10%. It is very interesting to remark that nevertheless the small specimens curve have been rescaled in order to make possible to compare results, a certain dependence on specimen size remains. Also the effect of skin thickness has been evaluated. Due to the global panel thickness has been kept constant, the variation of skin thickness causes a variation of H.C. core thickness. In Fig.4 it is possible to see that an increment of the skin thickness generates an increment of about 8% of the peak load. This is an expected behavior because the load peak mainly depends on instability phenomena. Hence reducing the core thickness (but maintaining the same height of the panel) leads to a structure that suffers less instability problems.

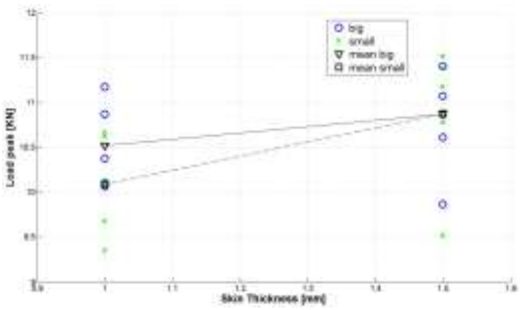

Fig.4. Effects of skin thickness on experimental load-displacement curve: load peak.

2.3 Statistical analysis of the results

In order to quantify the effect of each tested parameters on the results, also a statistical approach has been used. Using the ANOVA framework it has been possible to verify the influence of parameters from a statistical point of view. In Tab.4 are summarized the results of ANOVA analyses. It is important to underline that the ANOVA method can be applied only if the basis hypotheses are satisfied. In case some of these hypotheses are not verified it is still possible to apply the ANOVA technique but it is necessary to use a wider confidence interval. The drawback is an increment of the probability that some parameters will be considered like they don't affect results but actually they do. In present research this issue happens only for the effect of planar specimen size on the initial elastic slope. In these case the ANOVA method cannot be applied because at least one of three basis hypothesis has not been respected. We preferred to keep the confidence interval fixed at 95%, that is a very common value for many application and accept the possibility that for some parameters the ANOVA method cannot provide statistical reliable results.

responses / *factors*	**Load peak**	**Adsorbed energy**	**Plateau average load**	**Initial elastic slope**
Velocity (strain rate)	Yes	No	No	Yes
Skin thickness	Yes	Yes	Yes	No
Planar specimen size	No	Yes	Yes	-

Tab.4. ANOVA analyses about the effect of various parameters on the load-displacement curve

3 Low velocity impact on sandwich panel: experimental tests and numerical model

Experimental low velocity tests have been carried out using a free fall apparatus. The experimental set-up consisted into a guide tube and an impactator. The impactator was made falling inside the tube and in this way it was possible to generate low velocity impacts. There were the possibilities to modify the fall height and the impactator mass in order to evaluate impact with various energy (about 20-150J). The impactator nose was a sphere with 25.4mm diameter. The damage shape on the impacted panels have been measured with a coordinate measure machine in order to obtain the experimental damage profile. A numerical micromechanical model has been built aiming at the reproduction of these experiments. The FE model has been developed based on 3D solid elements with reduced integration (C3D8R) for the H.C. core. The upper and lower metallic skins have been made with brick elements. Interaction between plates and core has been done using a kinematic constrain which imposes the same displacements at the nodes coupled. Due to the strong non linearity, the analysis has been performed in dynamic explicit framework using an almost static approach as described in the ABAQUS documentation [7]. The impactator (has been modeled as a discrete rigid sphere with associated the inertial property of the fallen mass. Upper skin have a mesh of 0.78x0.78mm in the impact zone. A coarser mesh has been used far from the impact region. Lower skin mesh is coarser than the upper one, having mesh dimension of 10x10mm. Three element in the thickness have been used for both skin. The H.C. has been made by two part. The region nearest to the impact has been done with a refined mesh with 0.2x0.2x0.1mm mesh. The region of the core, around the refined central zone, has been meshed with a coarse mesh of 1.18x1.37x0.1mm. The two H.C. part have been connected each other, and with the skins, using a tie constrain. In order to reduce the calculation time, the model is smaller than the real one. Looking at the experimental acquisition of the damage profile it has been possible to define panel side length of 220 mm that is involved in damage. The real experimental value instead was 400 mm. The Al2024 skins have been modeled using a Johnson-Cook constitutive law and also a ductile damage criterion it has been added. The material calibration of the aluminium skins have been done through a complete experimental\numerical campaign on flat specimen in tension. In particular the calibrated damage criterion is based on a fracture locus which is an hyperbola having an asymptote for a triaxiality of -1/3. The approach is the same developed in [8]. Data are summarized in Tab.5.

Al 2024 JC constitutive law		**Al 2024 Fracture locus**		**Nomex dependence from strain rate**	
$\sigma=A+B\varepsilon^n$		$\varepsilon_f=D/(\eta+1/3)$		**Strain rate [1/s]**	**Yielding point [MPa]**
For each ε		D	0.144	0	40
A	335.1 MPa			5.26	44.52
B	511.6			15.78	45.16
n	0.4524			26.315	45.17
E	68710 MPa			36.84	45.18
ν	0.33				

Tab.5. JC and fracture locus parameters for skins; H.C. properties as function of strain rate

For what concern the mechanical properties of the H.C., Nomex calibration data have been obtained from [2] but there has been a significative modification including strain rate effect investigated in the previous part of this work. At present, strain rate effect has been considered increasing only the yielding point of the NOMEX as a function of strain rate. Strain rate level has been preliminary evaluated on the honeycomb compression rate. This is a preliminary and approximated approach and It is based also on the conclusion of [10]. The choice of the variation of yielding point as function of strain rate has been done keeping the same perceptual increment that can be evaluated in Fig.2a. It is important to underline that in order to avoid numerical instabilities, the softening effects which happens for a velocity higher than 500mm/min it has not been considered. In Tab.5 it is possible to see the selected values to describe strain rate effect on yielding point. In Fig.5 it is possible to see a comparison between numerical and experimental damage profile for various impact velocity. The FE model is able to reproduce the damage profile with a reasonable accuracy (error always below than 20%). The numerical model also provide conservative results because it estimates a maximum penetration higher than the experimental ones. The discrepancy between experiments and numerical model can be reduced adopting a more complex and complete numerical characterization of the mechanical properties of the Nomex. At present only the yield stress as function of strain rate has been approximately considered but other parameters, like elastic modulus, can be considered in future analyses to account for strain rate effect. However the numerical micromechanical models are able already to provide satisfactory results. It’s important to underline that the numerical model requires high computational cost. At present each analysis required about 18 hours of elaboration on a workstation with 8 CPU having a frequency of 3.8Ghz and 8Gb of RAM.

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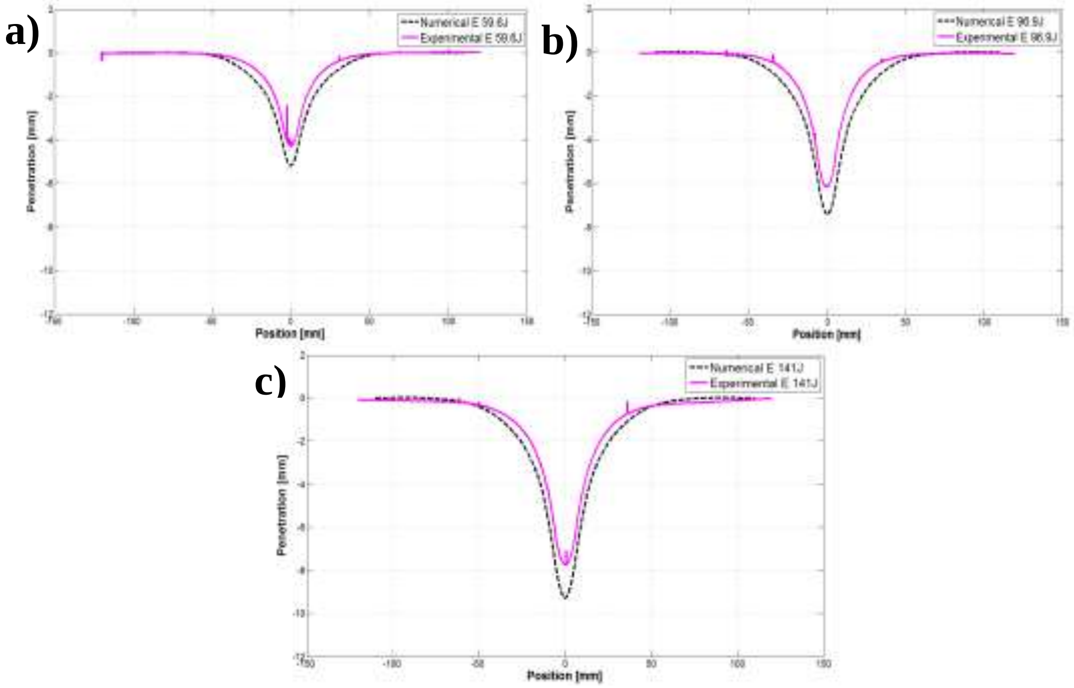

Fig.5. Comparisons between the experimental and numerical damage shape at various energy impacts

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