EXPERIMENTAL AND NUMERICAL STUDY OF THE ENERGY ABSORPTION CAPACITY OF PULTRUDED COMPOSITE TUBES

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ABSTRACT

A numerical and experimental investigation was carried out in order to evaluate the response of composite tubes, made of poly-vinylester or polyester matrix reinforced unidirectionally with glass fibers, under quasistatic loading. The influence of triggering in failure and energy absorption was investigated. Also a series of finite element models was created using LS-DYNA3D and compared with experimental results. The correlation between simulations and experiments was relatively satisfactory and from the results of the study the energy absorbing suitability of each tube was evaluated.

Results would provide more data that are needed for designing effective energy absorption mechanisms subjected under high speed loads.

1. INTRODUCTION

The increasing interest in safety and crashworthiness of structures leads to additional design requirements in automotive, aerospace and other applications were high energy absorption is required such as protection of civil structures under blast loading. Structures are often protected by claddings made from ductile materials absorbing energy due to plastic deformation energy absorbers are fabricated from metallic materials.

Due to superior strength to weight ratio and because of the flexibility in manufacturing composite materials are becoming more popular in replacing conventional materials. Pultruded composite sections have relatively high strength and stiffness in the longitudinal direction, debonding of the fibers is a procedure that absorbs high amount of energy during the different failure modes. As a result tubular sections may be considered as effective energy absorbers when subjected to quasi-static, impact or blast load in the axial direction.

A large number of studies have been conducted to investigate the progressive collapse of tubes under axial compressive impact or quasi-static loading. Research is focused on metal, composite and hybrid tubes. In the past studies were focused on metallic tubes where the mechanism of energy absorption is based on plastic deformation and different geometries are evaluated experimentally and numerically [1, 2]. Recently research is focused on composite tubes because of the different failure mode and the advantages described above [3, 4, 5, 6]. Mamalis et al. [4, 5] investigated the collapse of thin square FRP tubes, with variation in thickness, by experiments and also finite element simulations. An important factor is the lay-up of the tubes which can affect the energy absorption and it is part of the study of Han et al. [7]. In order to establish large amount of energy absorption in composite tubes it is important to trigger the failure and create a stable crush zone [3, 6] Thuis and Metz have made a study of different triggering configurations. Finally further studies combining the above are made for composite tubes [7, 8, 9] investigating different geometries, the lay-up, the speed of load and other parameters trying to combine the characteristics of composites and metallic materials in one energy absorber. Han et al. [7] have focused on numerical study and all the conclusions are made in detailed numerical models. Song et al. are investigating composite wrapped metal tubes experimentally and by an analytical model [8]. The study of Guden et al. is experimental and is focused on the effect of using hybrid tubes under quasistatic load [9].

In the present work the effect of different types of triggering and geometries is studied experimentally and numerically on composite pultruded tubes under quasistatic loading. This is the first step of an extensive research focusing on blast load where the results would provide more data for designing more effective energy absorption mechanisms subjected under high speed loads.

2. EXPERIMENTS

The specimens were two types of composite cylinders and one type of square tube. The outer diameter of the circular tubes was 38mm and 50mm and the thickness was 3mm (Figure1). The square tubes had outer width of 60mm and a thickness of 4.5mm, all the tubes had 100mm length. The circular tubes were made of poly-vinylester matrix reinforced with glass fibers and the square tubes were made of glass fiber reinforced polyester. The fibers were unidirectional. Two types of triggering were studied, 45^o edge chamfering (type 1) and corrugated pattern (type 2) that can be seen on Figure 2. In triggering type 2 the choice of the angle was made according to the maximum specific energy absorption. The optimum angle in the circular tubes was 60^o and in the square tubes 20^o.

Table 1

	Circular tubes(L = 100mm)		Square tubes(L= 100mm)
45^o edge chamfering (triggering 1)	Dout = 38mm Din = 32mm	Dout = 50mm Din = 44mm	b = 60mm t = 4.5mm
Corrugated pattern (triggering 2)	Dout = 38mm Din = 32mm	Dout = 50mm Din = 44mm	b = 60mm t = 4.5mm

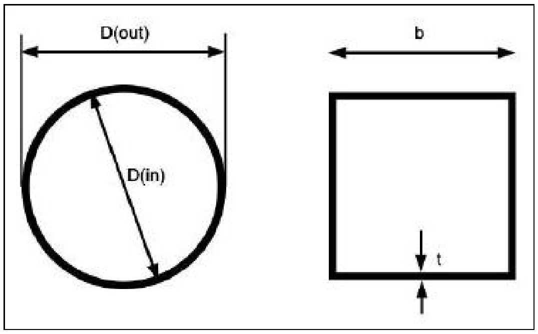

Figure 1: Dimensions of the profile

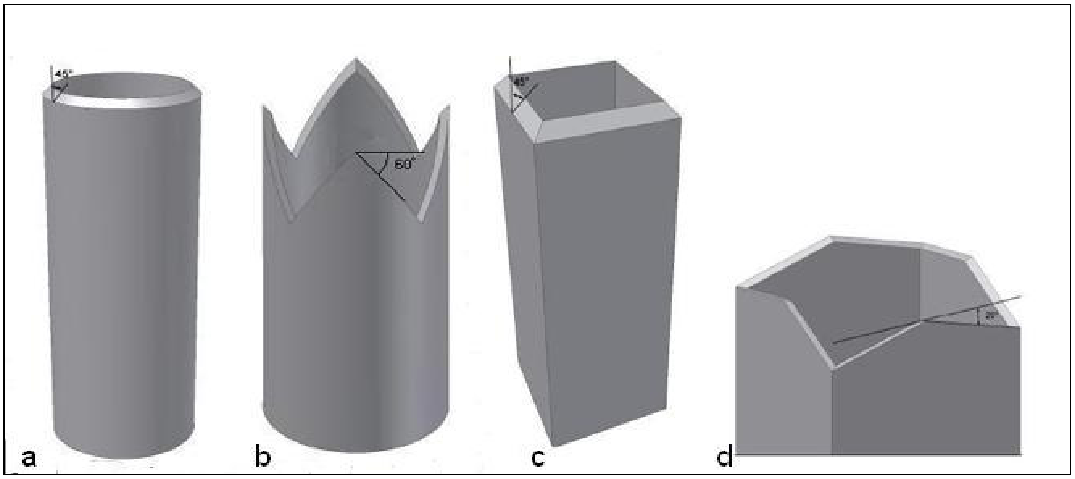

Figure 2: a, b. circular tube with triggering type 1 of 45^{o} and type 2 of 60^{o}. c, d. square tube with triggering type 1 of 45^{o} and type 2 of 20^{o}.

For the experiments a 100KN INSTRON 4505 was used. The velocity of the compression test was 200mm/min.

Force versus displacement was measured and the specific energy absorption was calculated from the formula:

$$E_S = \frac{E_d}{\rho L_S} = \frac{\int_0^{L_S} F dL}{\rho L_S} \left[\frac{J}{kg} \right] \quad (1)$$

Where *Ed* is the dissipated energy, *Ls* is the deformation length, *F* is the force and ρ is the linear density of the tube. The specific energy was calculated for 50 mm crushing.

3. NUMERICAL MODELLING

The LS-DYNA [10] code was used in conducting all the simulations. For all the models shell elements were used, simulating the different types of triggering. The Belyschko–Tsay quadrilateral element was used to model the tubes. The meshed shell elements were located at the mid-plane of each tube and in case of triggering 1 for all the models the top edge of the tube had an angle of 45^{o} in order to simulate the initiation of the damage.

3.1. Material Model

The material model 54 of LS-DYNA was selected to model both the tubes. Material model 54 has the option of using either the Tsai–Wu failure or the Chang–Chang failure criterion for assessing lamina failure. The Chang–Chang criterion is the modification of the Hashin's failure criterion [7].The post-failure conditions in the Material 54 model simulates four types of failure (i.e., tensile fiber mode, compressive fiber mode, tensile matrix mode and compressive matrix mode). If fiber breakage and/or fiber matrix shear failure occurs in a lamina, both the lamina's transverse modulus and minor Poisson's ratio are reduced to zero, the change in the longitudinal modulus and shear modulus follows the Weibull distribution. If matrix failure occurs either in tension or compression, then the transverse modulus and minor Poisson's ratio are reduced to zero, while the longitudinal modulus and shear modulus remain unchanged [7].

The mechanical properties of the tubes are given in Table 2. The properties were measured after conducting tests on specimens made by the same material of the tubes.

Table 2. Material model parameters

Density (kg/m^3)	ρ	1900
Longitudinal modulus (Pa)	Ea	33.5e+09
Transverse modulus (Pa)	Eb	8e+09
In-plane shear modulus (Pa)	Gab	5.5e+09
Out of plane shear modulus (Pa)	Gbc	5.5e+09
Minor Poisson's ratio	vab	0.29
Longitudinal tensile strength (Pa)	X_T	400e+06
Longitudinal compressive strength (Pa)	X_C	200e+06
In-plane shear strength (Pa)	S_C	25e+06

3.2. Boundary Conditions

The bottom of the tube was constrained by the *RIGIDWALL_GEOMETRIC_FLAT command in order to simulate the plane where the tube is standing on while the modeled upper end was free and subjected to compression by a moving plate. The loading plate was modeled as *MAT_RIGID. The density of both loading plate and tube were scaled up by factor 1000 for the purpose of computation efficiency, while still maintaining a quasi-static condition [7, 11]. It was observed that the ratio of the total kinetic energy to the total internal energy was less than 4% during the crushing process. The loading plate was displaced using the *BOUNDARY_ PRESCRIBED_ MOTION_ RIGID command at a constant rate of 200mm/min. The contact algorithm *CONTACT_ CONSTRAINT_ NODES_ TO_ SURFACE was used to simulate the boundary conditions between the plate and the tube.

4. RESULTS

In the Figures 3 to 8 the comparison can be seen between numerical and experimental results. Visually the deformation of the circular tubes matches with the deformation in the experiments. In the square tubes there is no initiation of failure in the corners of the geometry as it was observed in the experiments and it is one of the reasons that the numerical curve differs from the experimental (Figures 7-8).

Comparison of the force vs. displacement curves shows relatively good agreement between the numerical and the experimental results. In all numerical models the peak force was more or less the same with the peak force in the experiments. On the other hand the prediction of the absorbed energy for a crushing distance of 0.05m is not very accurate as it can be seen in Table 3, one of the main reasons is that no friction mechanism was taken into account and also the use of shell elements in combination with the material model do not simulate accurately the mechanisms of fracture and delamination.

The effect of triggering can be seen on Table 3 and Figure 9. The tubes that absorb the most energy are the square with triggering 2 and the 38mm circular with triggering 1. In order to choose energy absorber for high velocity impact from quasistatic testing the most effective tubes are the two circular tubes(38mm and 50mm) with triggering 2 because the force is not increasing rapidly and it is easier to initiate the failure. In general triggering 2 is most effective in initiating damage.

Table 3. Absorbed energy for 0.05m crushing distance

	Experimental	Numerical	Difference
38mm_triggering_1	2377.22 Joule	1804.56 Joule	24.08%
38mm_triggering_2	1882.95 Joule	1873.95 Joule	0.47%
50mm_triggering_1	1918.04 Joule	1529.51 Joule	20.25%
50mm_triggering_2	1108.73 Joule	1478.23 Joule	24.99%
Square_triggering_1	2157.85 Joule	2452.70 Joule	12.02%
Square_triggering_2	3498.15 Joule	2733.68 Joule	21.85%

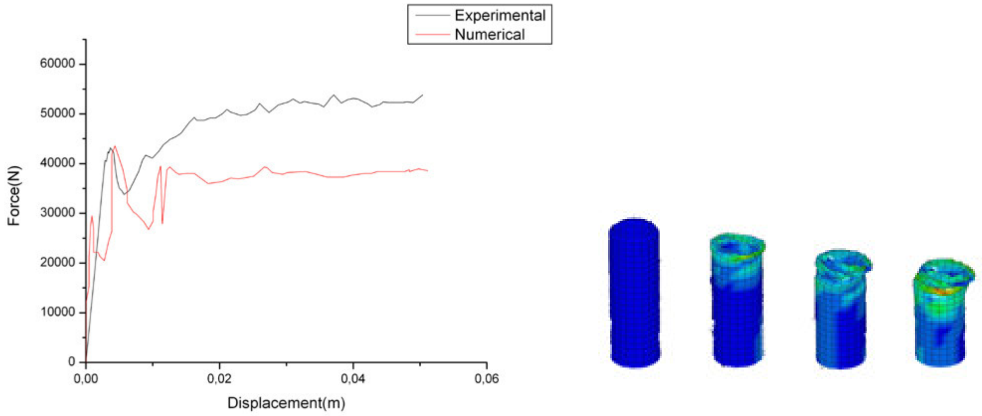

Figure 3: The force vs. displacement for the tube of 38mm with triggering 1.

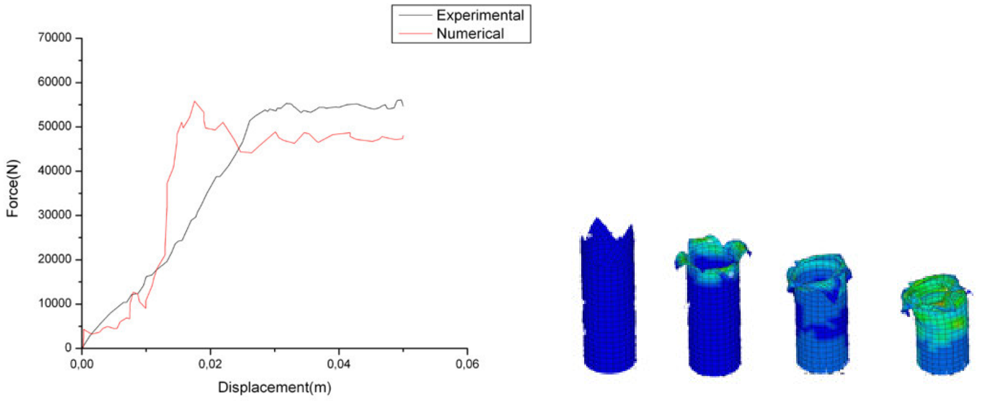

Figure 4: The force vs. displacement for the tube of 38mm with triggering 2.

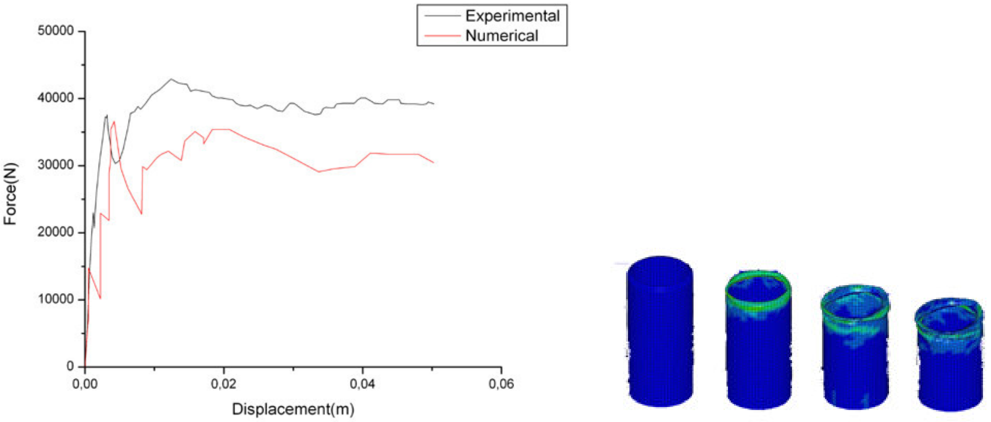

Figure 5: The force vs. displacement for the tube of 50mm with triggering 1.

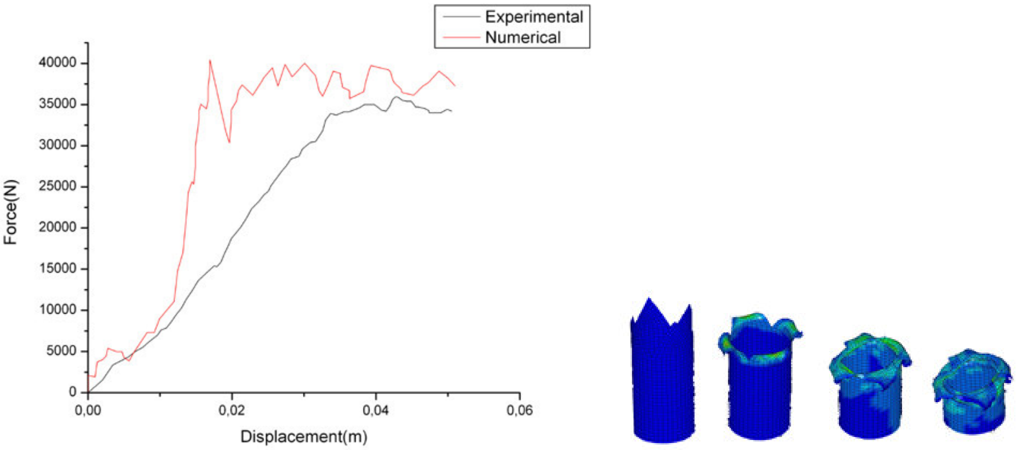

Figure 6: The force vs. displacement for the tube of 50mm with triggering 2.

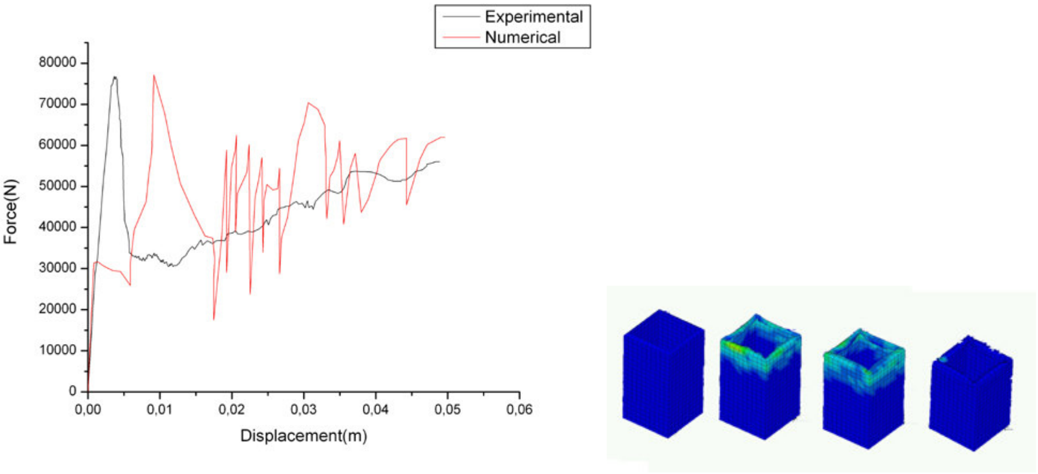

Figure 7: The force vs. displacement for the square tube with triggering 1.

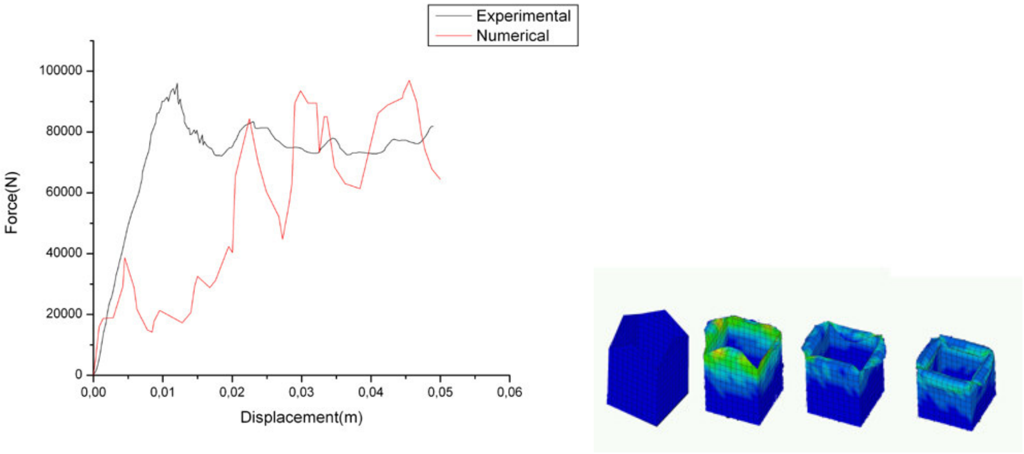

Figure 8: The force vs. displacement for the square tube with triggering 2.

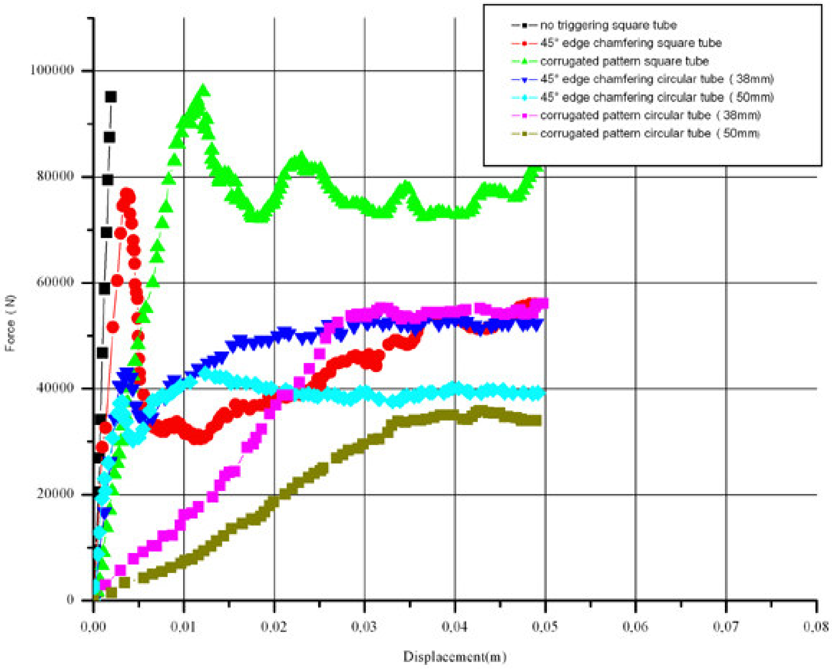

Figure 9. Experimental load-displacement curves.

5. CONCLUSIONS

Summarizing the results of this study it was found that finite element analysis can be used as a design tool and is able to give relatively accurate results considering that the finite element models are simply designed and are mainly based on the mechanisms of material model that was used. The results from this study can be used for further research on impact and blast load in order to choose an effective energy absorber. It was observed that the two circular tubes with triggering 2 seem to be the most effective ones because the peak force is low and not reached rapidly as a result the energy absorber will be deformed easier. The experimental results give also an estimation of the force that is required to achieve failure and initiate the damage.

REFERENCES

1- S. R. Guillow, G. Lu, R. H. Grzebieta, “Quasi-static axial compression of thin-walled circular aluminum tubes”, *International Journal of Mechanical Sciences* 43 (2001) 2103–2123.

2- M. Langseth, O. S. Hopperstad, T. Berstad, “Crashworthiness of aluminum extrusions: validation of numerical simulation, effect of mass ratio and impact velocity”, *International Journal of Impact Engineering* 22 (1999) 829}854.

3- A.M. Elgalai, E. Mahdi, A. M. S. Hamouda, B. S. Sahari, “Crushing response of composite corrugated tubes to quasi-static axial loading”, *Composite Structures* 66 (2004) 665–671.

4- A. G. Mamalis, D. E. Manolakos, M. B. Ioannidis, D. P. Papapostolou, “Crashworthy characteristics of axially statically compressed thin-walled square CFRP composite tubes: experimental”, *Composite Structures* 63 (2004) 347–360.

5- A. G. Mamalis, D. E. Manolakos, M. B. Ioannidis, D. P. Papapostolou, “The static and dynamic axial collapse of CFRP square tubes: Finite element modeling”, *Composite Structures* 74 (2006) 213–225.

6- H. G. S. J. Thuis & V. H. Metz, “The influence of trigger configurations and laminate lay-up on the failure mode of composite crush cylinders”, *Composite Structures* 25 (1993) 37- 43.

7- Haipeng Han, Farid Taheri, Neil Pegg, You Lu, “A numerical study on the axial crushing response of hybrid pultruded and ±45 braided tubes”, *Composite Structures* 80 (2007) 253–264.

8- Hong-Wei Song, Zhi-Min Wan, Zhi-Min Xie, Xing-Wen Du, “Axial impact behavior and energy absorption efficiency of composite wrapped metal tubes”, *International Journal of Impact Engineering* 24 (2000) 385}401.

9- M. Guden*, S. Yu¨ ksel, A. Tas_demirci, M. Tanog˘lu, “Effect of aluminum closed-cell foam filling on the quasi-static axial crush performance of glass fiber reinforced polyester composite and aluminum/composite hybrid tubes”, *Composite Structures* 81 (2007) 480–490.

10- LS-DYNA keyword user’s manual, V971, LSTC, Livermore, CA, 2007.

11- Feixia Pan, Jiansen Zhu, Antti O. Helminen, Ramin Vatanparast, NOKIA Inc., “Three Point Bending Analysis of a Mobile Phone Using LS-DYNA Explicit Integration Method”, *9th International LS-DYNA Users Conference.*