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State of the art of the passive pedestrian safety simulation

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Analysis and modelling

ABSTRACT

Purpose: In this paper we want to describe the work of Design Methods' research group of Dept. of Mechanical Engineering of Salerno University, in the research sector concerning passive pedestrian safety for vehicles, taking into account models FEM used and developed for vehicle design and optimization.

Design/methodology/approach: Our carried out models show a very good degree of Numeric/Experimental correlation, and also we've numerically certified our virtual impactors, designed following EEVC-WG17 requirements. These impactors have been tested at higher speed and we have had a good correlation, even if some difficulties there was, regarding the critical behaviour of the foam that covers some impactors, solved following different model-design optimization methods.

Findings: Best results obtained and described in this paper are relating to impactors modelling and certification, and Experimental/Numerical correlation of crash tests.

Research limitations/implications: The reaching of the elevated pedestrian safety performance, compatibly with the others, sometimes conflicting, performances, is one of the main targets to reach for the automotive industry by now and, above all, for the future.

Practical implications: Statistic studies carried out during last decades have underlined as pedestrians - with a prevalence of children and elderly - are a category with great risk of die in car accidents, especially during the collision with the front part of motor vehicles, particularly in the urban areas: according to recent investigations of a research committee of the European Community (CEC 2001), the risk of death in case of accident is, for pedestrians and cyclists, equal respectively to 9 and 8 times vehicle occupants' one.

Originality/value: In such a context, this paper is intended to study the pedestrian injury at the impact with vehicles and methods of designing and constructing vehicles in order to reduce the damage itself.

Keywords: Impactors' modelling; Simulation methodology; Design methodology; Pedestrian safety

1. Introduction

All over the world and especially in United States, between 1977 and 1991, research centres connected with automotive industry, and generally motor vehicles, took care in processing numerous statistical studies about accident between vehicles and pedestrians, with obvious regard to damage typology suffered by pedestrians.

The awakening of public bodies and private business to this concern started systematic studies on the problem of pedestrians' passive safety as shown by the numerous scientific articles and by the proposal draft of European Committee about new homologation criteria for automotives of the future, taking care of pedestrian safety.

In such a context, the pedestrian injury during impact with vehicles and methods of designing and constructing vehicles have been studied, in order to reduce the damages.

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For determining the entity of damage on pedestrians we refer to the measurement scale called Abbreviated Injury Scale (**AIS**) (see Figure 1) that the Association for the Advancement of Automotive Medicine (**AAAM**) [NHTSA, 2002], during the last twenty years, has developed in order to analyse the problem of the pedestrian safety and recognize required changes on vehicles to improve their safety, especially passive safety.

Using this scale, accidents reported in statistics were evaluated and they came to an agreement in considering injury that exceeds the level AIS = 3 mortal for the pedestrian.

AIS O	"No Injury"
AIS 1	"Minor Injury"
AIS 2	"Moderate Injury"
AIS 3	"Serious Injury"
AIS 4	"Severe Injury"
AIS 5	"Critical Injury"
AIS 6	"Maximum Injury"
AIS 7-9	"Unknown"

Fig. 1. AIS

Studying case history we found predominance of impact on some body parts instead of others, as shown in Figure 2; we especially note a great incidence of "child" pedestrians' death (see Figure 3).

Because of these problems, the European Community plans out restrictive regulations for vehicle homologation; these regulations have to consider the effects of pedestrian impact; the set of rules, that are not yet effective, is exposed in a proposal draft which describes conditions for performing tests, impactors' features simulating human body, measures to carry out and homologation limit value.

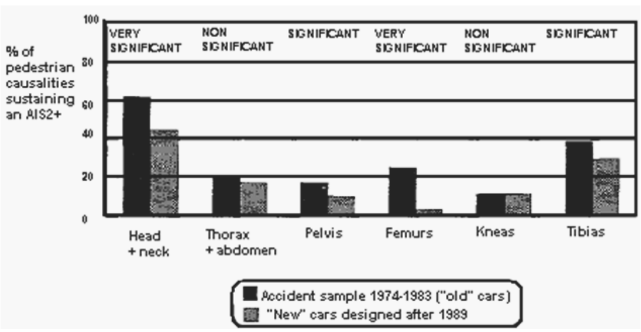

Fig. 2. Pedestrian AIS2

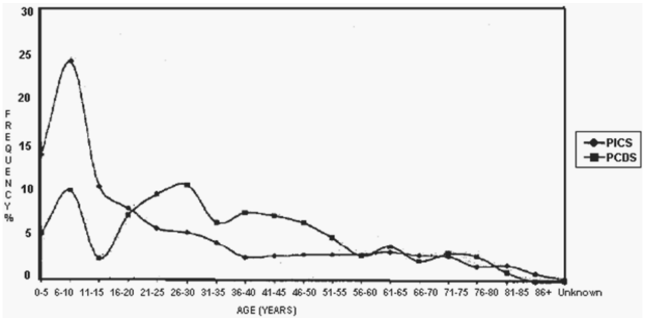

Fig. 3. Age distribution

In this paper we refer to that proposal draft, in order to define the simulation models and use FEM impactors' models.

Therefore, statistic studies carried out in the last decades have underlined how pedestrians, prevalently children and elderly men, are a high risk category in the car accidents, in particular in the urban areas: according to a surveying by European Community research committee (CEC 2001), the risk of death for pedestrians and cyclists because of street incidents is 8, 9 times as high as one of the occupants the motor vehicle.

From statistics one finds that the greatest part of these incidents is caused by collision of the pedestrian with the front part of motor vehicles, and this fact heavily influenced considerations about pedestrian passive safety: the reaction to this problem has caused a detailed research study by specific Working Groups of the EEVC (European Enhanced Vehicle-safety Committee), focused on characteristics of vehicle front part design.

After all EEVC studies, in order to evaluate pedestrian damage, caused by a motor vehicle, scientists proposed three kinds of impactors, for different tests (see Figure 4):

- Legform on bumper: to simulate the leg impact on bumper,
- Upper-legform on bonnet and on bumper: to simulate the pelvis impact on bonnet/bumper,
- Headform on bonnet: to simulate the head impact on bonnet.

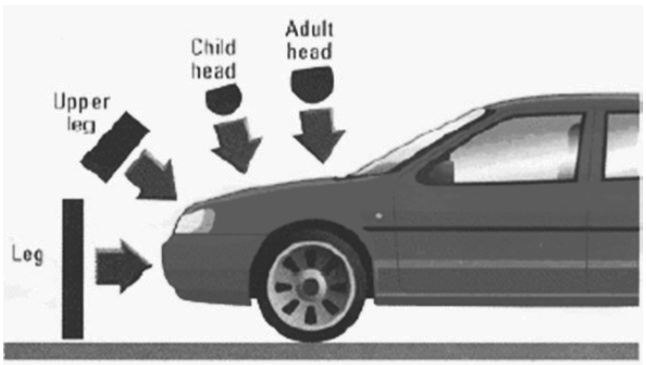

Fig. 4. Pedestrian tests according to WG17 - EuroNCAP

The F.E.M. software is used for the tests simulation, in order to reduce costs and times necessary to the pedestrian tests realization. The initial steps involved F.E.M. models definition, in order to reproduce elements that play fundamental role in the phenomenon: impactors and cars.

The aim of this work is to describe the state-of-the-art of the work of Design Methods' research group of Dept. of Mechanical Engineering of Salerno University, in the research sector concerning passive pedestrian safety for vehicles.

2. Description of work methodology

This work consists in describing the state-of-the-art regarding vehicles design, within pedestrian safety environment, taking care to finite element methods (FEM) and models used for vehicle study and development.

The full part of our information comes from our research group in industrial design of the Dept. of Mechanical Engineering, University of Salerno, which for five years has developed researches about pedestrian safety. Our principal results are reported below.

3. State-of-the-art about the passive pedestrian safety

3.1. General remarks

In this section there is the description of the most important results presented in several papers and conferences.

Below we report these research results, organized by topics divided in impactors' modelling, simulation methodology and design methodology.

3.2. Impactors' modelling

The Salerno University research group has found out that a statistical approach, based on the variance analysis, allows appraising the influence of the foam CF-45, that covers ACEA/NCAP leg impactors, on the results of the tests required for the safety of the pedestrians in case of accident [1-2].

These impactors are respectively covered by one and two layers of Confor Foam Blue CF-45 (25 mm thick), because this material exhibits similar mechanical behaviour of human flesh. For virtual simulations and prediction studies on the behaviour of new cars in Pedestrian Test, we have modelled the impact phenomena and characterized the CF-45 material properties by simulating them by an explicit FEM code. The explicit FEM code chosen for this work was PamCrash because of historical and business reasons. Material library of PamCrash contains a good model (Solid Type 22) for representing the mechanical behaviour of the foam.

Figures 5 and 6 show elaborated results and corresponding variance.

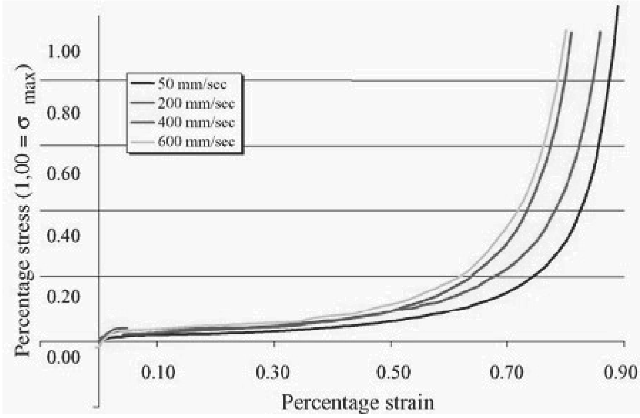

Fig. 5. Foam tests results

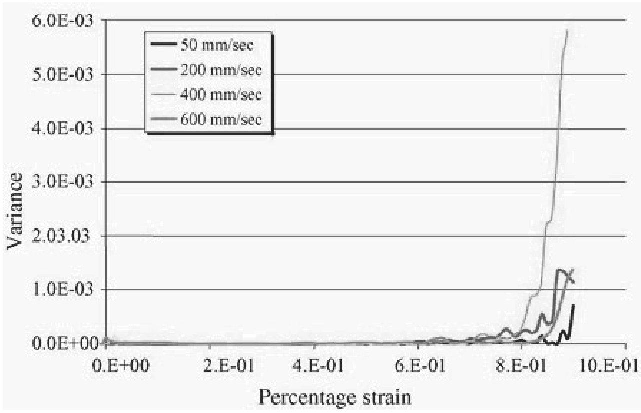

Fig. 6. Variance vs. deformation

The selected values of deformation define the necessary groups for the analysis of the tension. They are selected realizing a kind of blocking, operation that will also have repeated for the other types of test-tubes, and that drift from an attentive observation of the experimental curves. In effects, it is clear that a statistical analysis in general and especially a variance analysis is so much more necessary and somehow interesting as better it is the disorder between the curves, and consequently, between the points of deformation. For this reason we have defined the points of deformation with a bigger density in the final part of the curve, where the dispersion increase of the points of the corresponding curves to a date abscissa.

Once gotten the groups of the values of tension, a variance analysis is performed in the groups for which the experiment is relative to a not-varied ANOVA, as the term is unique and it is represented by different levels of speed and with a determined number of observations for each deformation.

If we analyse for example some kinds of foam, we note that they present a very complex structure, and we realize that it is difficult to develop a physical model, and even more difficult to build a numerical model representing the tested foam [3].

Results more in harmony with the reality could get with statistic or fuzzy methodologies, or with methodologies, however, derived from the theory of the information, that allows the best use of the information drawn from the experimental proofs or from the theoretical models that our potentiality allows us to develop [4-5].

This testing methodology, which represents a very particular case, because of his realization by an hydraulic back controlled facility for achieving a constant strain rate during tests, have given results easily to use in Explicit FEM codes, and allowed a very good numerical/experimental correlation using simple numerical and FEM models.

We have to do the same tests with higher strain rate (i.e. higher controlled compression velocity) in order to achieve good results in simulation at higher compression velocity (crash velocity, 10 m/s); we've to use the modified Hopkinson Bar, in order to achieve this results.

3.3. Simulation methodology

The simulation methodology has produced valid results, because of certification's tests simulation has provided homologated results and the correlation with experimental tests on vehicle was good.

The Lower-leg Impactor in PamCrash environment has been simulated, using the ESI impactor as starting shape and modelling the knee joint, that uses two cinematic joints with the same properties of the human knee joint.

The Numeric/Experimental correlation is not so good because of the critical behaviour of the kinematic joints in PamCrash when the forces are not perpendicular in respect to the leg axis.

For this reason, our research group have modelled a new very complicated kinematic joint not using the definition of PamCrash but simulating the complete mechanical behaviour of TRL impactor's knee joint, in order to obtain a good correlation.

All dimensions of parts of Legform such as mass, inertia, center of gravity and so on, are modelled in respect of the norms' requirements.

We have also calibrated the stiffness and the viscosity of real joint using the characterisation made for ESI impactors.

The impactor is made by two rigid bodies covered by one CF 45 foam characterized at low and high speed. The rigid bodies are linked each other by a cinematic joint as described in Figure 7.

We have also calibrated the stiffness and the viscosity of real joint using the characterisation made for ESI impactors.

The knee joint modelling has allowed to certificate the impactor and to test the impactor on a real case of pedestrian impact, in order to correlate the experimental test on a vehicle (2003) [6]. All the Output parameters are into the certification ranges, as shown respectively by following Figures 8, 9, 10.

The model is simple and useful to be utilized in a full-scale test simulation (pedestrian impact), because its time step is upper than 0.6 µs and there are not hourglass, mass increasing or distortions problems in output files.

In reference papers of period 1977 - 1997 and in EEVC documents, the scientists describe a proposed homologative test for child/adult head impact; it is represented by an impact simulation of some standardised impactors on car bonnet, in order to evaluate the child/adult head injury as deceleration of their gravity centre.

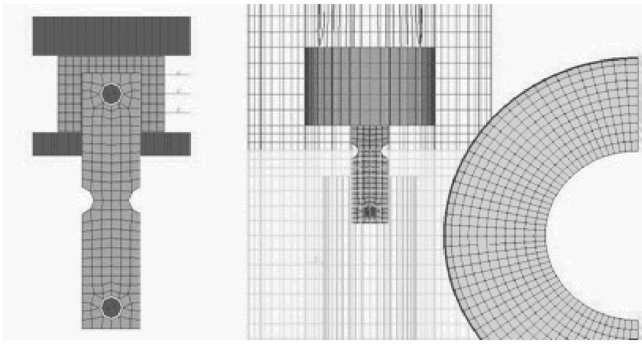

Fig. 7. Lower leg knee joint FEM model

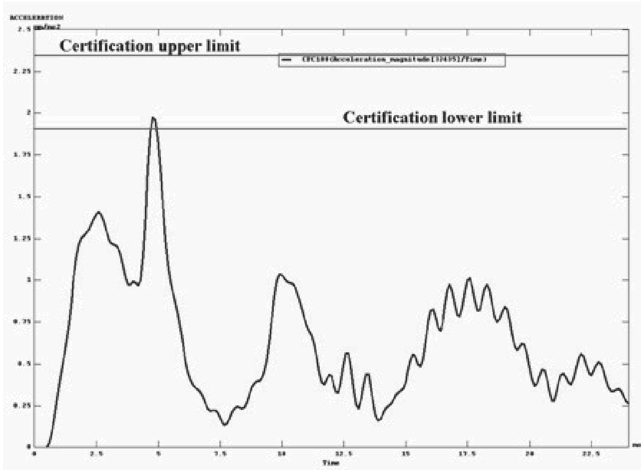

Fig. 8. Acceleration certification

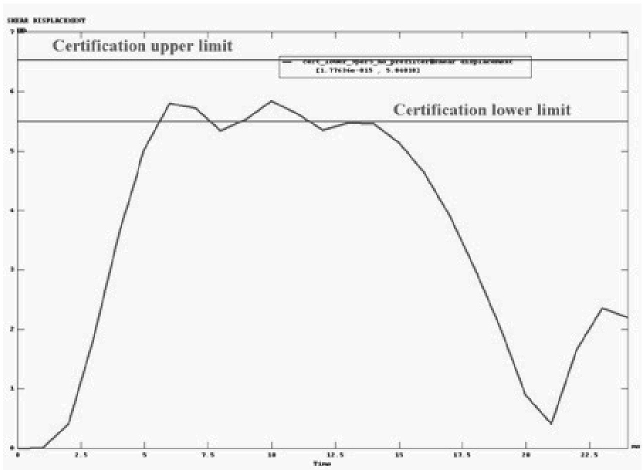

Fig. 9. Shear displacement certification

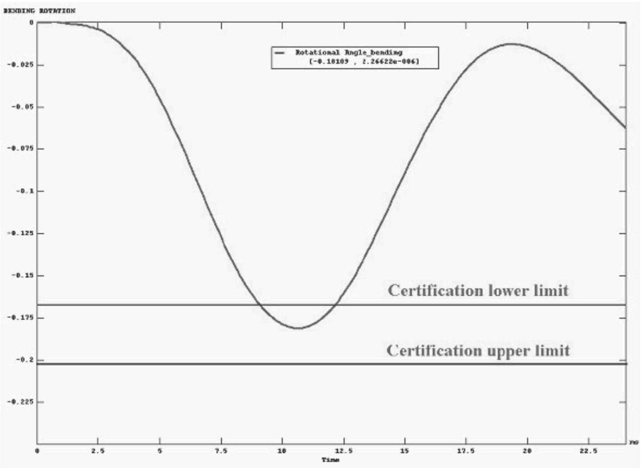

Fig. 10. Bending angle certification

Injury evaluation criteria is an energy criterion and is quantified by the HPC index (Head Performance Criteria also called, without distinction, HIC – Head Injury Criteria) defined as follows:

$$HPC = \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a dt \right]^{2,5} (t_2 - t_1) \max \qquad (1)$$

in which t_1 and t_2 are respectively initial and final impact's instants (t_2 - t_1) is the integration range and a is acceleration resultant vector, measured by an accelerometer mounted in the head-impactor.

The attention on Child Head impact phenomena (the high priority impact both for WG17 and for ACEA protocol) and on the factors that affect the increase of HIC values has been placed. Other studies had demonstrated that in the middle area of the bonnet, the acceleration peak, that heavily affects the value of HIC, strictly depends on "structural" parameters of the bonnet; one of our research group's paper is based on this studies and has reproduced, using numeric simulation, the Child impact dynamic (a very low-energy impact....only 150 Joule), in order to demonstrate the importance of kinetic phenomena despite of the deformation's one.

We have justified the validity of formulated hypothesis by the comparison of impact simulation of ACEA and WG17 test; these protocols are different for impactor mass and impact speed.

Child Head impact simulation in accordance with WG17 protocol was made and correlated to physical tests made on a FIAT Punto 60 by TNO (with an average correlation index of ±10%) (2003) [7].

The test simulated, for the evaluation aim of our study, was made on a sub-system composed by the complete bonnet with its catch and hinges and was simulated in the explicit FEM code PamCrash.

Output results are shown in the following Table 1.

Table 1.
Output results

	HIC	Max acceleration (mm/ms2)	Displacement (vector magnitude) bonnet skin (mm)	Displacement (vector magnitude) bonnet frame (mm)
02 experimental test WG17	992.2	2.069	-	-
03 experimental test WG17	906.2	2.065	-	-
02 WG17 test simulation	920.2	1.951	51.1	56.4
03 WG17 test simulation	992.7	1.836	48.1	51.9
02 WG17 subsystem test simulation	950.3	1.966	50.1	54.8
03 WG17 subsystem test simulation	938.8	1.802	55.5	58.6
02 ACEA subsystem test simulation	556.0	1.419	60.2	60.2
03 ACEA subsystem test simulation	438.8	1.231	66.1	66.1

Subsequently, a new impactor has been modelled, in order to respect the indication given by new homologative norms, but especially to make good experimental/numerical correlation in our experiment tests, both for Child and for Adult Head impactors.

The new FEM models have the same number of finite-elements as the oldest one (ESI 2003) and have a very good stability in calculation, both in certification tests and in experimental test on bonnet.

We've performed, with the same FEM model, chid and adult head, in order to obtain a good experimental/numerical correlation and to be sure that our head is certificated by EEVC documents, and can be used to perform tests on Fem model of Vehicles, as shown in Table 2.

The more important part of the work is the certification of impactors and their testing on a real case of pedestrian impact in order to correlate the experimental test on the vehicle (2004) [8].

Table 2.
Simulation results

Our impacors	Test Result [G]	Lower Limit [G]	Upper Limit [G]
Adult Head	385	337.5	412.5
Child Head	416	405	495

Our research group after the work of impactors' modelling (legform and upper legform ones) has tested the Impactor by the simulation of the Certification Tests, as described in the EEVC and EuroNCAP norms, in order to obtain the same results of the experimental test. The Numeric/Experimental correlation is very good and we had numerically certified our impactor.

	CERTIFICATION VALUE		MISURED VALUE
	Min	Max	
Force Peak	1.20 kN	1.55 kN	1.32 kN
Difference Between The Peak Forces		0.10 kN	0.01 kN
Max Middle Bending Moment	190 Nm	250 Nm	201 Nm
Max Bending Moment (Upper – Lower)	160 Nm	220 Nm	173 Nm
Difference Between The Upper And Lower Peak Bending Moment		20 Nm	2,8 Nm

Fig. 11. Certification results

We have also made several tests at higher speed, whose experimental results are published, and we have obtained some correlation problems because of the critical behaviour of the flesh at high speed simulation, but the results on different cases show the same output behaviour, giving us an instrument to solve that problem (2004) [9, 10].

The final obtained Certification results for the upper leg impactor are shown in the Figure 11.

3.4. Design methodology

Our research group has developed a work focused essentially on vehicle configuration and on material's characteristics in the predictable impact zone of pedestrian and on the vehicle.

For child head impact, the aim of the work was to create, the same condition of first phase of impact, in which local stiffness plays the main rule of the game, realizing a test-case by using a CAD-CAE parametric/variational model of car-bonnet, as shown in Figure 12 [11].

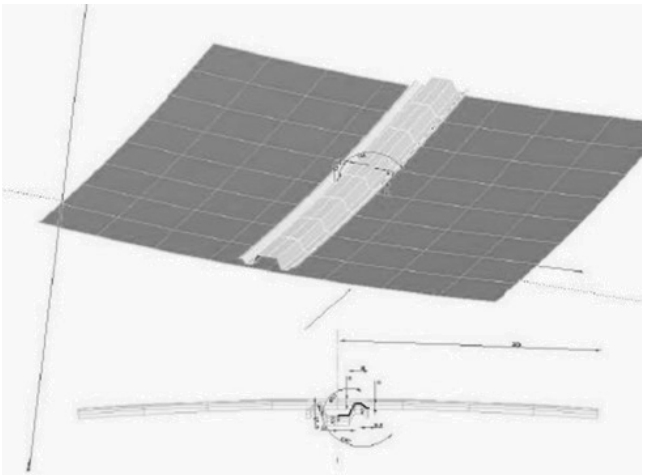

Fig. 12. Parametric/variational model

Moreover in another work we investigated how energy absorption in head impacts, and therefore HIC value, is influenced by the capability of free deformation of the hood, that depends from the distance of the under bonnet elements – engine parts, battery, suspensions domes, other structural parts – from the bonnet itself, as shown in Figure 13, and how to compensate the effects of these elements through its rigidity.

Fig. 13. Distance between dome and bonnet frame

Our final purpose consists in determining the optimal combination between these two parameters (bonnet stiffness and free deformation space), in order to reduce the aggressiveness of the car front part in case of pedestrian impact (HIC values possibly under 1000), without excessively penalizing other performances - particularly the containment of volumes, weights and therefore fuel consumptions - that are the most important required performance for a new car [12].

In conclusion, it's evident that the basic parameter to reduce head impacts injuries is the availability of enough underbonnet space, so that the bonnet can absorb naturally the necessary impact energy. More precisely, from numerical simulations results, it came out that at least 45-50 mm of underbonnet space are needed for child head impacts, while they increase up to 70-75 mm for adult head. Those values are corresponding to results of experimental studies afforded in past times (H. Zellmer e K.P. Glaeser, The EEVC-WG 10 Head Impact Test Procedure in Practical Use, 1994; A. Otobushin e J. Green, An Analytical Assessment of Pedestrian Head Impact Protection, 1998).

Another research developed by our group proposed a new method based on virtual reconstruction of the surface which envelopes all the deformation surfaces in internal part of the bonnet. The deformed shape of bonnets has been evaluated using FEM explicit code PamCrash. Using a Pre-processor, we have reconstructed, starting from a points' (FEM model's nodes) clouds, a new surface of maximum deformed bonnet. This surface was processed and rapid prototyped as a puzzle of shells with their support. A finished piece is shown in Figure 14.

Fig. 14. Prototyped tile under measurement machine

This prototyped surface was super-imposed on the real under-bonnet layout of car and will allow easily evaluating where and how much our deformed bonnet could hit the hard-parts of the Engine Layout. Our results have shown a new easy and fast method to evaluate the potential performance of the front part of a vehicle in Child head impact only reconstructing, with a reverse engineering operation, the bonnet shapes (surface) and, after a simple processing, rapid prototyping the deformed bonnet-shape, in order to avoid to take all the under-bonnet layout with a reverse engineering operation, that could be more difficult and very time-consuming.

This approach cab be used in early design step, in order to optimize the under bonnet layout and reinforcements.

We want now just remember that relief with a reverse engineering system all the under bonnet layout of a vehicle is quite impossible because of the complexity and the different reflectivity of the surfaces due to very different materials used.

Obtained results are very good: the final prototyped models are very good and their errors in respect of CAD/STL models are very small (maximum error measured was 0.58 mm; medium error is 0.2 mm), in spite of some macroscopic errors happened during 3D-printing operation in extremities of prototyped pieces. Procedure is quite fast and allows to obtain good results with very low costs; the whole procedure makes possible to obtain a very good defined triangularized surface that can be printed by the RP Machine [13, 14].

4. Conclusions

In this paper we underline the development and certification of pedestrian impactors presented by our research group; actually there are a few of certified impactors' model in few FEM software (Pam Crash, Radioss, LS-Dyna, Madymo) [15].

The most important research results are reported, regarding the finite elements dynamic simulation in passive safety environment. Particularly, impactors modelling and certification are in the first rank, besides studies for improving the vehicle performances within pedestrian safety environment [16].

In the following Figure 15 we can see an example of post processed vehicle FEM model.[17].

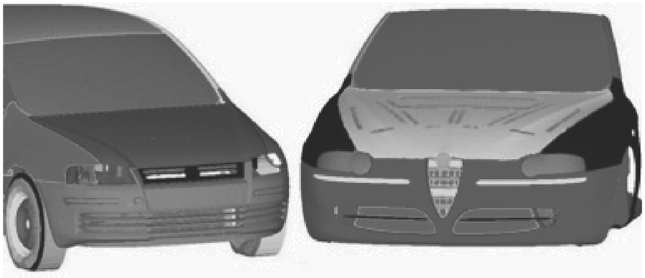

Fig. 15. Vehicle FEM model

In our work we underline the great importance of the simulation approach: by numerical calculus it's possible, also thanks the high computational power of the modern workstations, to find out principal factors that influence the degree of aggressiveness of the front part of the vehicle and therefore to make some changes on such parameters already in the early phase of car design, with meaningful advantages in terms of times and costs.

Best results obtained are concerning Style and Layout design lines for improving the vehicle performances within pedestrian safety problematic. The results come from our research group in industrial design of the Dept. of Mechanical Engineering, University of Salerno, which for five years has developed researches about pedestrian safety. Most of these studies was carried out in collaboration with Fiat research centres.

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