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Study and modelling of the passenger safety devices of an electric vehicle by finite elements

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Abstract

Electric mobility gets mainly involved quadricycles and cars. Between these two vehicle types there are differences in terms of stability, performance, cost, autonomy and safety. The authors studied the implementation of passenger safety devices on a prototype for an electric vehicle derived from a heavy quadricycle. A finite element analysis starting from experimental results was carried out in order to determine the effectiveness in case of frontal and side crashes.

Keywords: passenger safety; electric vehicle; ULV; FEM modelling

1. Introduction

Nowadays electric mobility is an attractive challenge because of its low environmental impact. Furthermore, small dimensions of the vehicle are researched in order to move in the cities. Electric Ultra-Light vehicles (ULV) match these requirements although their low safety performances stated in EuroNCAP (2016). This work aims to evaluate the possibility to improve the passenger safety of an ULV prototype deriving from a heavy quadricycle. The car would cost more than a heavy quadricycle and less than a small electric car and has a pioneering tubular chassis

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presented in Centro Studi Internazionali (2016) which induced the authors to establish the position of the curtain airbag.

Finite element models were used in order to simulate frontal and side impacts. Numerical simulations are indeed recently used in passenger safety studies because they allow the repeatability of the tests without high setup costs as declared in Hayashi and Taylor (2014).

In the 1960s some automotive engineers began to develop lumped element models mentioned in Leonardi (2012) in order to study vehicle dynamics. Kamal (1970) for example modelled a car with masses, springs and dampers. According to Pawlus et al. (2011) this model was simple but the estimation of the parameters for each component was a critical issue. Moreover, Leonardi (2012) highlighted the experimental data had low accuracy because of the devices.

In the 1970s in the aerospace field the Finite Element Analysis (FEA) was raising as demonstrated by Hughes (2000) and in the 1990s, FEA was being used in order to verify experimental data, as reported in Leonardi (2012).

Leonardi (2012) stated that the producers tried to find a way in order to reduce the production costs and Hill (2007) pointed out that a large amount of the cost was due to engineering and testing. The reduction of physical experiments was a possible solution: for a car, more than twenty tests are carried out and each one costs around 650.000 dollars as stated in Leonardi (2012).

According to Leonardi (2012), nowadays FEA and experimental tests were still carried out. In Teng et al. (2008) a multibody model of the occupant was used and a comparison between this model and a full-scale in LS-DYNA3D was executed. A multibody model of a vehicle was instead presented in Pawlus et al. (2011). Here the front part of the car was divided in six nondeformable components attached each other with springs and dampers. This model is worth only for frontal impacts at low speed supposing that the front part of the car is the only deformable zone in these types of crash.

Because of the high dynamics of the studied phenomena, explicit methods are commonly used as demonstrated in Midjena and Muraspahic (2013) and Borovinsek et al. (2009).

In the models presented in this work the belts were modelled, the airbags were instead designed. The combined action of these devices is strictly necessary because the airbag deployment could hurt the passenger as stated in Barman et al. (2008).

Furthermore, only the components of the car nearby the driver were in the models. In this way, an optimization of the computational cost was reached.

Nomenclature

x	longitudinal direction of the car, positive from the rear to the front
y	transversal direction of the car, positive from the passenger seat to the driver seat
z	vertical direction of the car, positive upwards
Δt	time step [s]
P_{ext}	pressure outside the airbag [Pa]
ΔP_{def}	difference of pressure for the opening of the vent holes [Pa]
a_R	head acceleration [g]

2. Materials and methods

An ODB (Offset-Deformable Barrier) crash and a SMB (Side Mobile Barrier) crash were simulated in the laboratory. During the tests, the accelerations of interesting points of the car were recorded. The dummy was not instrumented.

HyperMesh and HyperCrash were employed for the pre-processing activities, HyperView and HyperGraph for the post-processing. The calculation was carried out using an explicit method (Radioss). This scheme is conditionally stable and for this reason, the time step has to be less than a critical value. The user can manually define a critical value. When the calculated time step becomes less than the user-defined value, mass scaling occurs.

Shell3n, Shell4n, Tetra4 isoparametric elements were used. Rigid elements were employed for the connections.

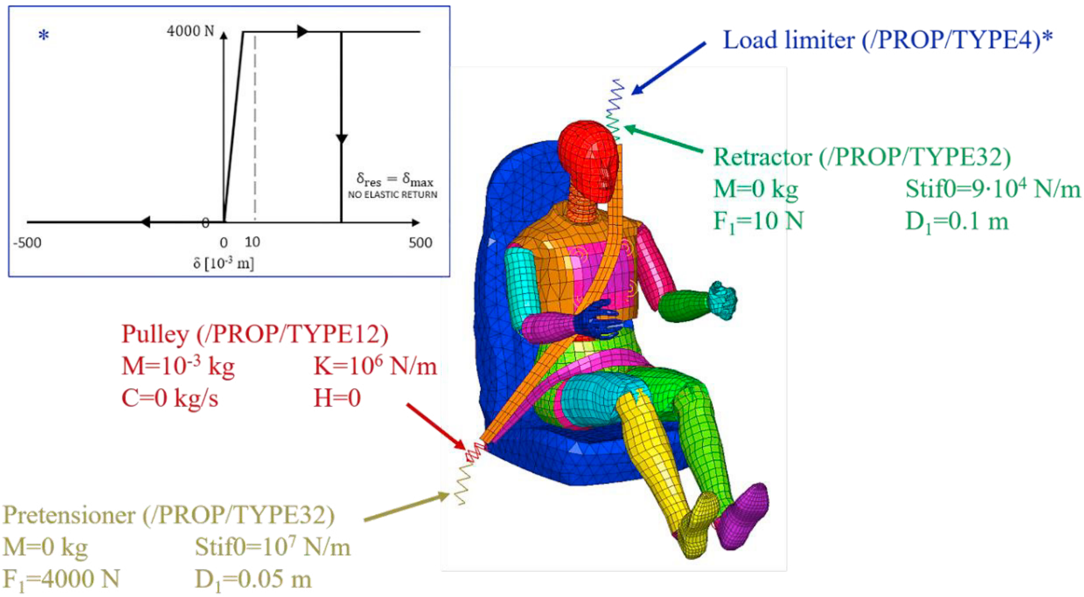

Fig. 1. Belts.

Springs elements (Fig. 1) were used in order to schematize the retractor, the pretensioner, the load limiter and the pulley (belt sliding). The specific cards available in HyperCrash were used, the numeric values were default or modified by the authors. Uniform pressure in the airbag, ideal gas behavior and adiabatic conditions were assumed during the deployment.

Pure nitrogen with the characteristics in Table 1 was assumed.

Table 1. Nitrogen properties, values from Altair (2009).

Properties	Value
Volumetric viscosity	1 kg / (m s)
Ratio of specific heats	1.4
Heat capacity at constant pressure	926000 J/(kg K)
Temperature	780 K

The mass flows in the two cases of impact are described in Fig. 2. These functions were taken from Neutz et al. (2009) and the modifications allowed easier and faster deployments.

The contacts were modelled using the card /INTER/TYPE7.

The effects of the restraint systems were studied on an Hybrid II 50th percentile male. His weight is 70 kg. Shell elements modeled the skin and had a very small density. The mass of the parts of the body were concentrated in the centers of gravity. Rigid elements linked these points to the relative shells. Springs with default properties are used for the joints. A line of shell elements nearby the waist was removed in order to let the chest bend.

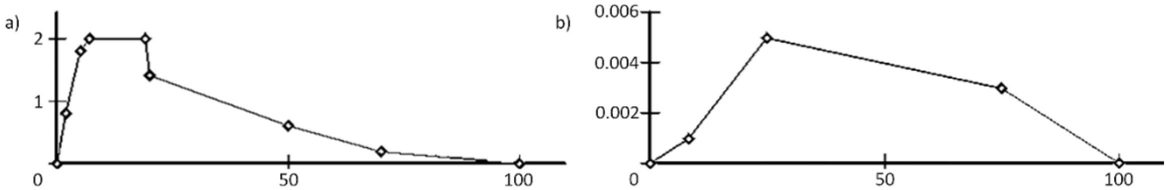

Fig. 2. Mass [kg/s] vs time [10^{-3} s] (a) frontal airbag; (b) side airbag.

Wheel, firewall, dashboard, floor		Pedals		Seats		Frontal airbag	
/ELAST		/ELAST		/FABRI		/FABRI	
ρ [kg/m^3]	1.00E+02	ρ [kg/m^3]	7.85E+03	ρ [kg/m^3]	43	ρ [kg/m^3]	850
E [Pa]	4.00E+09	E [Pa]	2.06E+11	E [Pa]	2.00E+07	E_{11} [Pa]	5.00E+10
υ	0.3	υ	0.3	υ	0	E_{22} [Pa]	5.00E+10
Door, chassis, roof		Windshield, window		E_1	0	υ_{12}	0.1
/PLAS_JOHN		/PLAS_BRIT		E_2	0	G_{12} [Pa]	1.00E+09
ρ [kg/m^3]	7.90E+03	ρ [kg/m^3]	4.00E+03	n	0	G_{23} [Pa]	1.00E+09
E [Pa]	2.10E+11	E [Pa]	7.50E+10	C_1	1	G_{31} [Pa]	1.00E+09
υ	0.3	υ	0.23	C_2	1	RE	1.00E-03
a [Pa]	2.00E+08	a [Pa]	3.90E+07	C_3	1	ZeroStress	1
b [Pa]	4.50E+08	b [Pa]	0	E_t [Pa]	2.50E+05	Curtain airbag	
c	0	n	0	υ_t	0	/FABRI	
ICC	0	σ_{max} [Pa]	4.00E+07	η_0	0.01	E_{11} [Pa]	1.00E+11
m	0	$\varepsilon_{t1}=\varepsilon_{t2}$	3.00E-04	λ	0	E_{22} [Pa]	1.00E+11
n	0.5	$\varepsilon_{m1}=\varepsilon_{m2}$	4.00E-04			G_{12} [Pa]	2.00E+09
ε_{max}	1.00E+30	$d_{max1}=d_{max2}$	0.999			G_{23} [Pa]	2.00E+09
σ_{max} [Pa]	4.25E+08	$\varepsilon_{f1}=\varepsilon_{f2}$	5.00E-04			G_{31} [Pa]	2.00E+09

Fig. 3. Material laws.

Before the simulation of a crash, it is necessary a dummy positioning phase. Explicit calculation is carried out in order to have the final position of the driver on the seat due to the gravity force. The dummy positioning phase lasted 0.4 s. The retractor was activated at 0.3 s.

The materials overwent the laws of Fig. 3. The materials of the dummy and of the seats belts were those provided by Altair (2009). For the meaning of each value refer to Altair (2009).

Orthotropic Shell property was assigned to the seat belts and the airbags. QEPH (Quadrilateral ElastoPlastic Physical Hourglass Control) formulation for the shell elements and HEPH (Hexahedron ElastoPlastic Physical Hourglass Control) for the solid elements were used in order to avoid hourglass phenomenon as suggested in Altair (2009).

2.1. Frontal impact

The unfolded frontal airbag was a circle with a diameter of 650 mm, border width of 15 mm and bag thickness of 3 mm. The maximum dimensions of the folded airbag had to be 130x100x40 mm. A tuck folding was used in two orthogonal directions. An iterative process was chosen in order to identify the folding lines. The piece of the airbag between the line and the outside had to be less than the distance between the airbag center and the folding line minus 5 mm until the prefixed dimensions of the airbag were reached. Minimum gap and minimum tuck width equal to 1 mm were assumed. The vent holes covered an undefined zone of 2500 mm^2: they opened as soon as the pressure inside the airbag became equal to $P_{ext}+\Delta P_{def}= 10^5+2\cdot10^2$ Pa as suggested in Altair (2009).

The model for the simulation of the frontal impact had the components rigidly linked. The master node was positioned under the driver seat (Fig. 4). The simulation consisted of three phases:

- Dummy positioning (400 ms, time step: 10^{-3} ms);
- Acceleration (100 ms, time step: 10^{-4} ms, the system linearly reached the impact velocity);
- Impact (300 ms, time step: 10^{-4} ms).

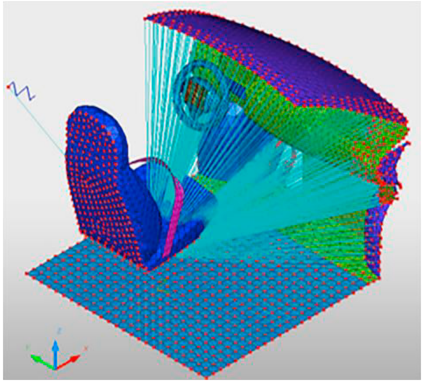

Fig. 4. Model frontal impact.

The pulse curves registered during the crash test nearby the driver seat were imposed to the master node. A gravity load was applied during the three phases.

Preliminary simulations carried out by the authors pointed out that a reasonable time to fire (TTF) values could be 15 ms. TTF is the moment in which the airbag deployment starts and the pretensioner is activated during the crash.

2.2. Side impact

A curtain airbag covering the anterior and posterior windows was installed in the model for the side impact. The border width was of 10 mm and the bag was 0.5 mm thick. The airbag was fitted as close as possible to the windows. The inferior side rotated 90° around a line at 550 mm from the inferior side of the airbag. Afterwards, a zigzag folding with minimum width of 5 mm, minimum gap of 1 mm and zigzag length of 50 mm was carried out. Other two open folds along two lines positioned 1030 and 1290 mm from the left side were accomplished in order to have a folded airbag with a shape similar to the A-pillar. Vent holes were not inserted in this model. TTF is set to 0 s after the crash beginning because a fast intervention of the airbag is requested.

The model used for this simulation is shown in Fig. 5. The major part of the components was rigidly linked. Another rigid connection was built only for the driver seat. In this way, the movement of this component due to the rupture of the bolts which fix the seat to the floor was modeled. A symmetry boundary condition was given to the nodes on the symmetry plane of the chassis and of the roof.

The arms of the dummy were removed in order to have the same situation of the experimental crash.

After the dummy positioning, the very impact was simulated (300 ms, time step: 10^{-4} ms). The acceleration in the y direction measured during the crash test nearby the driver seat was imposed to the master node of the car. It was assumed that the deformation of the door occurred in 50 ms with a constant velocity.

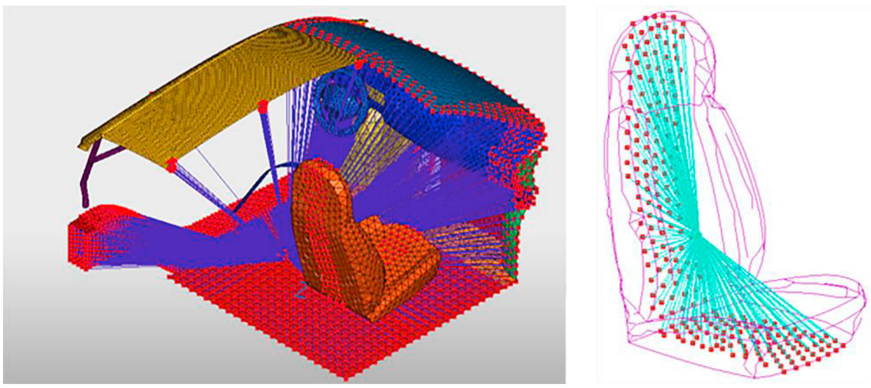

Fig. 5. Model side impact.

3. Results and discussion

The effectiveness of the restraint systems was evaluated using the *HIC* (Head Injury Criterion) parameter. It measures the probability of brain injuries and is defined by EuroNCAP (2011) as:

$$HIC = \max\left((t_2 - t_1)\left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a_R dt \right)^{2.5} \right) \quad (1)$$

Table 2. *HIC* limits, from EuroNCAP (2011).

	Frontal impact (with steering wheel airbags and passengers)	Side impact
Higher performance limit		
HIC_{36}	650 (5% risk of injury ≥ AIS3)	
Resultant acceleration 3 ms exceedance	72 g	
Lower performance and capping limit		
HIC_{36}	1000 (20% risk of injury ≥ AIS3)	
Resultant acceleration 3 ms exceedance	88 g	

Euro NCAP (2011) prescribes the calculation of HIC_{36}, where t_2-t_1=36 ms (t_1 and t_2 two times during the impact) and the limits for frontal and side impacts shown in Table 2.

The energy error was very small, around 0%, during the dummy positioning, with peaks of 1.90%. These values can be certainly considered acceptable.

3.1. Frontal impact

The results for the frontal impact are summarized in Table 3. The first column indicates the time after the beginning of the crash in which the interruption of the calculation occurred.

Table 3. Results frontal impact.

Component	Interruption [ms]	HIC_{36}	Acc. max. [g]	Err. % max	ΔM/M [%]
No restraint systems	95.6	6197.52	480.89	-24.2%	0
Only airbag	100.1	1182.08	191.39	-19.8%	2.2e-8
Only belts	No	9486.0	750.22	-45.0%	0
Airbag + seat belts	No	249.17	64.13	-13.7%	0

The results pointed out that the frontal airbag and seat belts are critically needed to prevent serious damages in case of impacts. Only in this case, rigid collisions between the driver and the car component did not occur (acceleration<88g and no interruptions of the calculation). In the second case, the dummy impacted with the deploying airbag while the only action of the belts did not avoid the collision of the head with the steering wheel making the energy error very big (the calculation tends to diverge).

3.2. Side impact

The outcomes for the second crash type are presented in Table 4.

Table 4. Results side impact.

Component	Interruption [ms]	HIC_{36}	Acc. max. [g]	Err. % max	ΔM/M [%]
No restraint systems	137.0	345.83	524.44	+4.0%	1.0e160
Only belts	No	804.84*	11.32	-3.4%	6.1e-3
Only airbag	No	102.05*	67.64	-10.0%	1.1e-2
Airbag + seat belts	No	156.23	70.90	-10.0%	1.2e-2

In the second case, an *HIC* value less than the limit imposed by Euro NCAP (2011) was reached. However, a deeper analysis showed that the chest impacted with the door before than the head. The chest had indeed an acceleration peak 30 ms after the crash beginning (Fig. 6). A parameter for the chest injuries could be considered but the authors chose to satisfy the more urgent limit. Even the position assumed by the driver at the end on the third case (Fig. 7) made the authors consider the airbag not sufficient in order to avoid damages. For these reasons, only the combination of belts and side airbag reduced the possible damages.

4. Conclusion

A numerical analysis highlighted the potentiality of the vehicle in reaching high levels of passenger safety. The implementation of the curtain airbag in a vehicle with a pioneering chassis was an innovative aspect.

The models used for the study, containing only some parts of the car, reduced the computational cost.

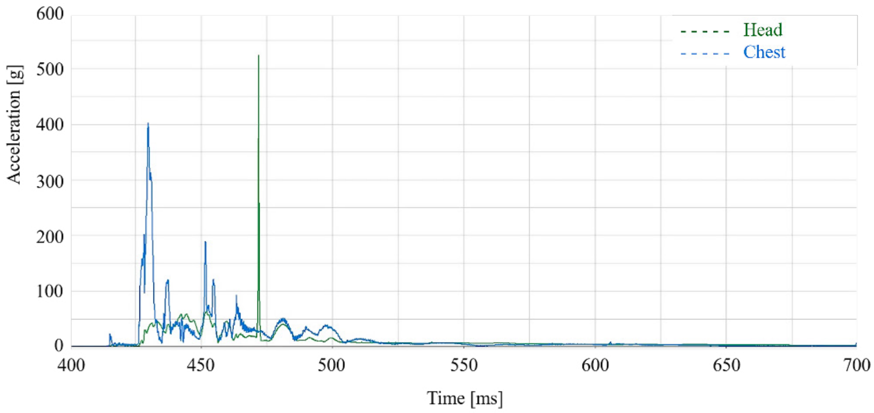

Fig. 6. Chest and head accelerations for the case with the only airbag.

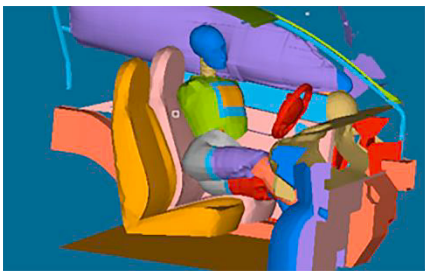

Fig. 7. Dummy position at the end of the third case.

During the building of the model, some simplifications for the geometry and the material laws were assumed and only qualitative comparison between the behavior of the dummy in the crash tests and in the simulations were possible because the dummy of the experiments was not instrumented.

Next studies could indagate the effects of the systems on other dummies and of the position of the driver.

Considering only one dummy and one position, restraint systems with fixed characteristics were implemented. Variable pretensioners, position sensors and airbag with variable volumes described in Mackay (1996) could be considered.

Further analysis about other types of impacts and other parameters for the evaluation of the effectiveness of the passenger safety devices could lead to interesting results.

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