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Research Article

Numerical-Experimental Assessment of a Hybrid FE-MB Model of an Aircraft Seat Sled Test

F. Caputo,[1] **A. De Luca**,[1] **F. Marulo**,[2] **M. Guida**,[2] **and B. Vitolo**[3]

[1]*Department of Engineering, University of Campania Luigi Vanvitelli, Aversa, Italy*
[2]*Department of Industrial Engineering, University of Naples "Federico II", Napoli, Italy*
[3]*Geven, Zona Asi Boscofangone, Nola, Napoli, Italy*

Correspondence should be addressed to F. Caputo; francesco.caputo@unicampania.it

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This paper deals with the development of an established hybrid finite element multibody (FE-MB) model for the simulation of an experimental sled test of a single row of a double passenger seat placed in front of a fuselage bulkhead, by considering a single anthropomorphic Hybrid II 50th dummy arranged on one of the seat places. The numerical investigation has been carried out by focusing on the passenger passive safety. Specifically, the occupant injury assessment has been quantitatively monitored by means of the head injury criterion (HIC), which, based on the average value of the dummy head acceleration during a crash event, should not exceed, according to the standards, the value of 1000. Numerical results provided by the hybrid model have been compared with the experimental ones provided by the Geven S.p.A. company and with the results carried out by a full FE model. The hybrid model simulates with a good level of accuracy the experimental test and allows reducing significantly the computing time with respect to the full FE one.

1. Introduction

Nowadays, the importance of passive safety is becoming even more important for the transport field to the point of influencing the design practice [1–3]. In fact, several experimental and numerical studies are addressed to investigate and improve the crashworthiness of vehicles by paying attention to the passengers' safety. Compliance with the passive safety specifications leads to a little increase of the vehicle weight, which can be tolerated in view of an increasing of the chance of survival in case of an accident.

In the aerospace field, several components, such as the seat system, have been completely redesigned in order to improve the capability of the aircraft to protect passengers during crash events. As crash event, it must be intended, for example, an emergency landing.

The vehicle crashworthiness can be measured also in terms of the occupant injuries [4–12]. Among the several parameters that can be monitored, the head injury criterion (HIC) one plays a key role, denoting possible head injuries [13–18]. HIC parameter, based on the average value of the passenger's head acceleration acting during a crash event, should be lower than 1000 in order to guarantee the passengers' safety. Another parameter is the maximum compressive load measured between the pelvis and the lumbar column of the anthropomorphic test dummy (ATD), which should not exceed 1500 lb (6.67 kN), or, if torso restraints are used, tension loads in individual straps should not exceed 1750 lb (7.78 kN) [1, 2].

Several experimental and numerical studies dealing with such matter have been proposed in literature: the former are characterized usually by destructive tests performed on such large instrumented full-scale structures such as aircraft, fuselage section, and seats, even equipped with ATDs, which cannot be easily repeated due to the high costs and the complexity of the tests, requiring often advanced laboratories, the use of complex acquisition sensor networks, complex and long result analysis, and so on. Concerning the numerical investigations, an established predictive numerical model can give a significant contribution in the assessment of passengers' safety, allowing to overcome all aforementioned issues related to experimental test. In particular, a numerical tool gives also the possibility, under a certification by analysis (CBA) approach [19–22], to perform optimization analyses aimed to virtually achieve the optimal structural solution, decreasing the number of experimental tests and the costs required for the developmental phase. Concerning the disadvantages, numerical simulation of crash phenomena involving ATDs needs a high computational power. Moreover, the establishment of the model requires facing with the assessment of the assumed assumptions as well as hypotheses, the improvement of the level of accuracy, and consequently, the availability of high computational power.

This paper investigates on the passive safety addressed to the aircraft seat system.

A well-designed seat should allow passengers to not entrap themselves independently and escape the aircraft, by leading to good chance to survive, after a crash. Standards that investigate on the realistic dynamic performance of aircraft seats can be found in literature in order to emphasize occupant impact protection and to analyse the full-scale aircraft impact tests.

This paper deals with an improved hybrid finite element multibody (FE-MB) model for the simulation of an experimental sled test of a single row of a double passenger seat placed in front of a fuselage bulkhead by considering a single anthropomorphic dummy arranged on one of the seat places. Tests have been developed at the laboratory of Geven S.p.A., which is equipped with a sled decelerator testing system compliant with certification requirements from the FAR25 for TSO C127a regulations [1]. The development of the proposed numerical model started from a preliminary hybrid FE-MB model presented by authors in [23]. Specifically, the new modelling has been carried out in order to improve the level of accuracy of the predicted passenger kinematics. The hybrid modelling strategy has been carried out in order to exploit both FE method level of accuracy and the lower MB computational costs [23]. Whilst in the MB approach, which requires less computational costs, the dummy is modelled by rigid bodies, defined by both mass and moments of inertia (connected by suitable characteristics joints); in the FE approach, the dummy is modelled by means of finite elements containing more details than the former, which lead to several difficulties in terms of model management and higher computational costs.

In a seat sled test, all components, such as dummy, seat, and restraint system, may be modelled by means of both MB and FE approaches, leading to a less or more accurate simulation, respectively.

FE codes allow a very detailed modelling of all components, such as safety belts, dummies, and structural parts, by leading to very complex models, which are usually characterized by several million of degrees of freedom with negative feedback on the computing time and on the model versatility. In fact, the management of small design changes implies strong efforts in terms of modelling.

On the contrary, the MB method, to the detriment of a less level of accuracy related to the nondeformability of the modelled components, can be helpful for designers to simulate quickly the structural response of a structure under several configurations. More properly, MB methods lend mainly themselves to the prediction of the kinematics of assembly components under complex loading conditions more than to the investigation of the stress-strain field.

As a matter of fact, this modelling method is widely used in a preliminary design stage where it is still interesting to investigate more structural solutions.

So in order to enjoy the accuracy of the FE method, as well as the low computational time provided by the MB method, the hybrid approach can be used, allowing improvement of the modelling where needed by means of the FE method as well as lowering the computational time. The lowering of the computational time can be achieved by considering the MB approach for the parts of the analysed system, whose deformations do not influence the dynamic system responses and for which only kinematic aspects must be taken into account.

In order to assess the prediction capability of the developed hybrid FE-MB model, the simulated biomechanical parameters, such as the acceleration of the head of the passenger, with the relative calculation of the head injury criterion (HIC) and the loads transmitted to his lower limbs have been compared with the experimental ones. Moreover, the predicted ATD trajectory has been compared with the trajectory simulated by a full FE model in previous papers [22, 23].

2. Experimental Dynamic Testing of Airplane Seats

The experimental test, provided by Geven S.p.A., is aimed to demonstrate the compliance of the seat passenger system with FAR 25.562 [1]. A Hybrid II 50th passenger dummy has been arranged on a double seat positioned in front of a relatively stiff bulkhead (Figure 1). The main parameter monitored during the test is the acceleration of the head, with the relative calculated HIC. The experimental test provided value of HIC higher than the limit one expressed in the standard. However, this aspect does not affect the purpose of determining a methodology for a numerical-experimental correlation.

The sled and passenger seat systems are launched at the prescribed speed against a steel bar deceleration system in order to reproduce the required simulation pulse. The resultant longitudinal deceleration over time is shown in Figure 2.

A dedicated test rig has been set up to reproduce the overall seat installation within the aircraft cabin. Prototype seat has been installed on the test sled with effective seat track. Proper seat belt installation required a test rig able to guarantee the correct position of aircraft/belt interface points with respect to the seat. Additionally, the test rig has been oversized in order to minimize the effects of any deformation occurring during the test.

2.1. Hybrid FE-MB Model. In a hybrid FE-MB model, the user diversifies the modelling, where possible, by integrating within the same solver rigid bodies with deformable finite element components, with the advantage of computing time reduction. The paper [23] reported an alternative strategy of simulation, named coupling, that as well as the hybrid one

Figure 1: Experimental test.

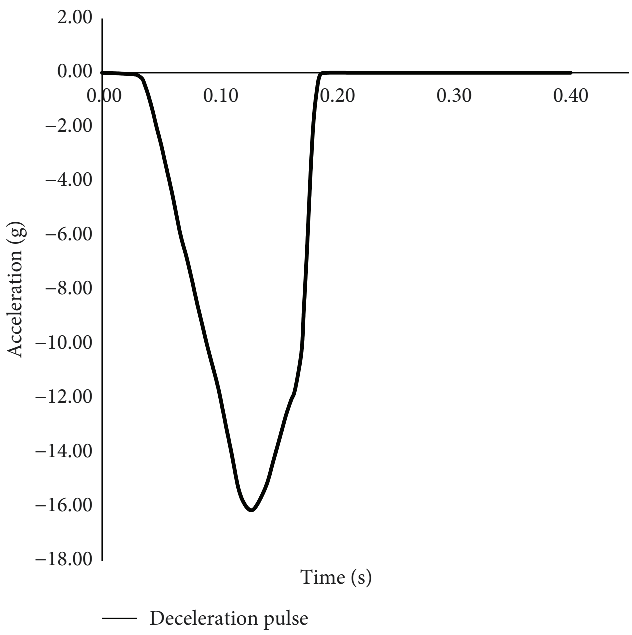

Figure 2: Resultant deceleration versus time curve characterizing the seat sled test.

gathers features and advantages of both FE and MB methods; according to this strategy, two separate solvers (one FEM and the other MB) work in parallel, exchanging information, and the connection between the software is represented by contact and constraint forces acting on the elements of the models. Generally, the effectiveness of these techniques lies in the combination of multibody versatility with finite element level of accuracy; these simulations are more flexible than full FEM. The hybrid method, contrary to the coupling approach, does not use an external FE code; for this reason, the computational costs are strongly reduced. Specifically, it has been assessed in a preliminary study [22, 23] that the simulation of the deformability of both seat and restraint system, which cannot be accomplished by means of the MB method, influences significantly the kinematics of the ATD during the seat sled test. This aspect can be empathised by comparing the ATD trajectory simulated by a full FE model (Figure 3(a)) with the trajectory simulated by a full MB one (Figure 3(b)). In fact, according to Figure 3(b), the ATD of the full MB model does not hit the bulkhead, unlike that of the full FEM (Figure 3(a)).

As a result, the modelling of the whole seat system by FEM, in the hybrid FE-MB model, appears to be the most efficient strategy to simulate the seat sled test. Consequently, the other parts, such as the ATD and the bulkhead, are modelled by means of rigid bodies according to the MB approach to reduce the computing time.

The improvement of this hybrid FE-MB model with respect to the one presented by authors in [23] lies in a different setup of the kinematic joints of the MB components. The interconnection structure of a multibody system depends strictly on the definition of the kinematic joints. The equations of motion (Newton-Euler) (1 and 2) of a rigid body, referred to its centre of gravity, are

$$m_i \ddot{r}_i = F_i, \tag{1}$$

$$J_i \cdot \dot{\omega}_i + \omega_i \times J_i \cdot \omega_i = T_i, \tag{2}$$

where m_i is the mass, J_i is the inertia tensor with respect to the centre of gravity, ω_i is the angular velocity vector, F_i is the resultant force vector, and T_i is the resultant torque vector relative to the centre of gravity. For each body, F_i and T_i include the constraint forces and torques due to joints which cannot be determined until the acceleration of the system is known, in contrast with all other forces and torques which depend only on position and velocity quantities. Equations (2) and (3) are multiplied by a variation of the position vector, δr_i, and a variation of the orientation, $\delta \pi_i$, and the resulting equations are summed for all bodies of the system.

$$\sum \delta r_i \cdot \{m_i \ddot{r}_i - F_i\} + \delta \pi_i \cdot \{J_i \cdot \dot{\omega}_i + \omega_i \times J_i \cdot \omega_i - T_i\} = 0. \tag{3}$$

When the variations δr_i and $\delta \pi_i$ of connected bodies are such that the constraints caused by the joint are not violated, the constraint forces and torques in joints will cancel.

The model has been developed within the TNO Madymo® software [24, 25] environment (Figure 4), which contains both MB and FE solvers. In the finite element module, solid hexa, penta, 1D beam, and shell elements can be chosen. However, since the Madymo is a native MB code, the FE module is not characterized by the same accuracy of other native FE codes, especially for 3D finite elements. Hence, in order to improve the precision of the simulations, it has been preferred to model the whole seat by means of shell element type for a total of 105,226 elements and 151,219 nodes.

The modelling of inertial properties of the seat system has been guaranteed by the definition of both materials' density and thickness for each shell element.

The adopted hybrid approach allows the use of different integration methods for the equations of motion for both FE and MB modules. For short-duration crash analyses, explicit integration methods are preferred.

The hybrid approach is in any case based on the assumptions that the parts considered rigid do not influence the behaviour of deformable parts [7]. The deceleration pulse (Figure 2) has been applied to the seat fixed to the slide, along the seat sled test longitudinal direction as shown in Figure 4. Gravity and initial velocity have been applied to all parts of the model. The test case selected for the experimental test consists of a metallic double seat, fabricated from aluminium 2024-T351 and 7075-T651 components. Cushions are made of foam material [26], which constitutive law has been shown in Figure 5 in true stress-strain. For each material, an elastic-plastic model has been selected.

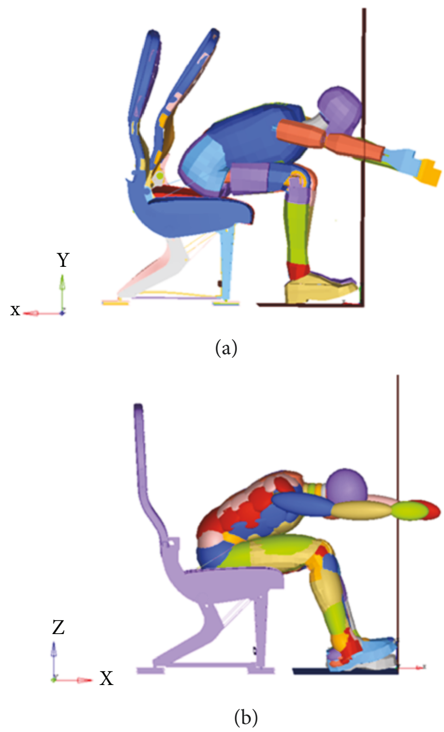

Figure 3: Full FE (a) and full MB (b) models.

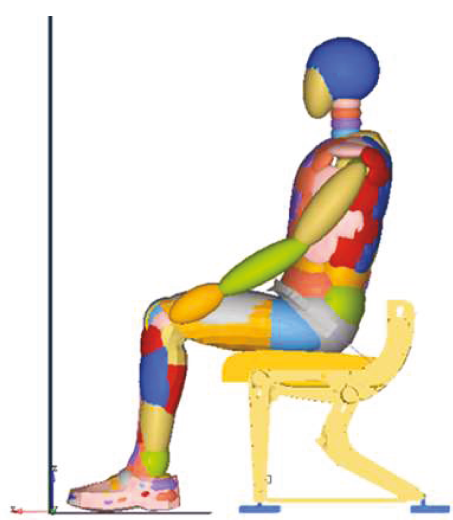

Figure 4: Hybrid model.

3. Results and Discussion

To assess the reliability of the proposed hybrid model, the head resultant acceleration has been numerically and experimentally monitored, allowing consequently the calculation of the experimental and predicted HIC values.

The numerical and experimental frames corresponding to the instant of time in which the ATD head hits the bulkhead are shown in Figure 6. According to Figure 6, it is possible to observe that the seat deformation (Figure 6(a)) is in good agreement with the predicted one (Figure 6(b)).

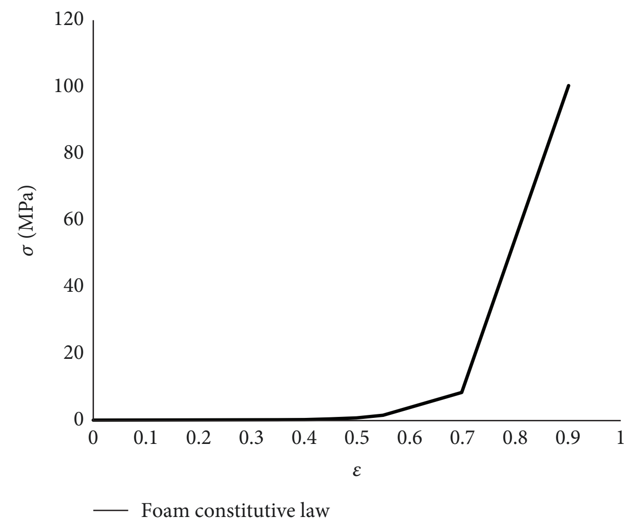

Figure 5: Foam constitutive curve.

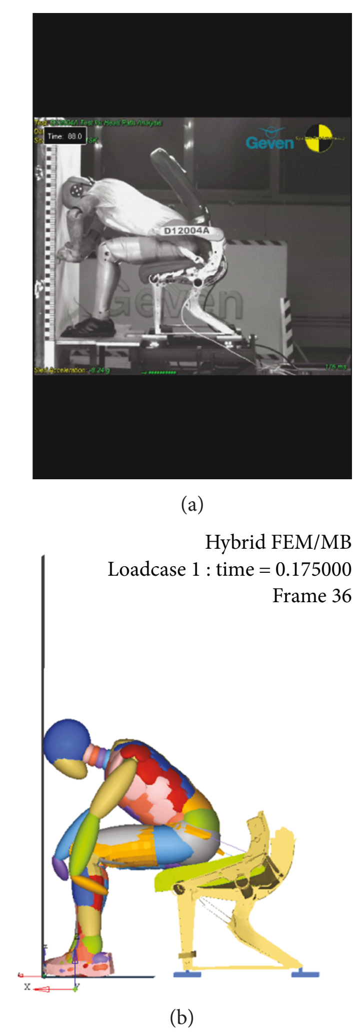

Figure 6: Experimental test (a) and hybrid model (b).

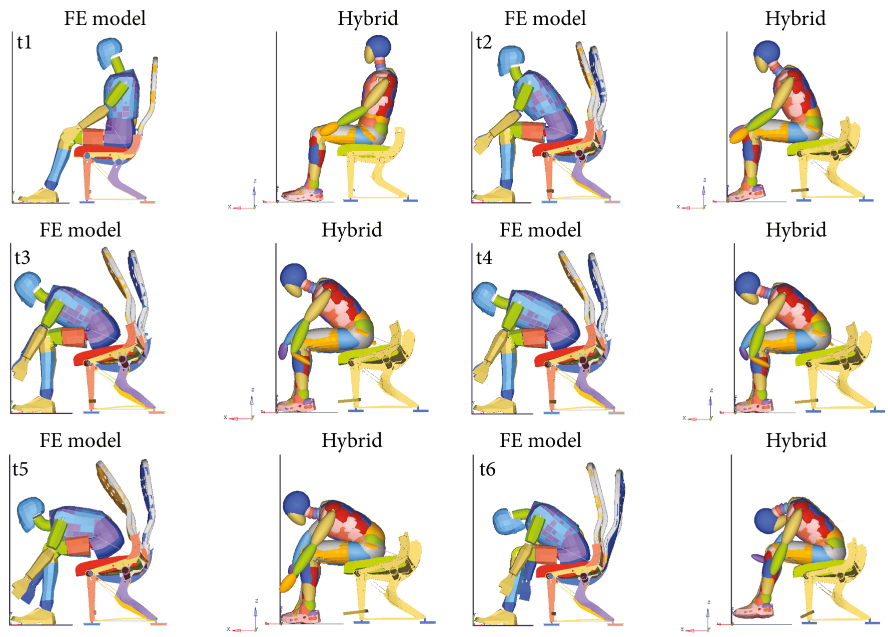

Figure 7: Full FE and hybrid model results.

Moreover, results of the hybrid model have been compared to those predicted by the full FE model presented by the authors in [22, 23]. Some numerical frames extracted by both full FE and hybrid models have been compared in Figure 7.

Figure 7 shows a good correlation in terms of seat system and ATD kinematics.

Moreover, the predicted head path, induced mainly by the effects of the deformation on the seat frame, has been compared with the experimental one in Figure 8.

According to Figure 8, a good level of accuracy can be noticed.

Concerning the head resultant accelerations, Figure 9 compares results provided by the experimental and numerical investigations. Acceleration versus time curves have been filtered with SAE filter 1000 [27]. For a better comparison, the numerical curves have been shifted a few milliseconds to make sure that their maximum occurs at the same instant as that of the experimental one.

From Figure 9, it can be noticed that even if all predicted acceleration peaks are well-predicted, the same cannot be said for HIC values. Specifically, HIC value carried out by the full FE simulation is significantly higher than the ones provided by the experimental test and hybrid model. The full FE overestimation can be attributed to the fact that HIC value is calculated by (4), which considers mainly the area under the full FE acceleration versus time curve larger than the other ones.

$$\mathrm{HIC} = \max\left\{(t_2 - t_1)\left[\frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} a(t)\,dt\right]^{2.5}\right\}, \quad (4)$$

where $a(t)$ is the resultant head acceleration measured in g and t_1 and t_2 are the extremes of the integration interval containing the head acceleration peak measured in seconds for the HIC calculation.

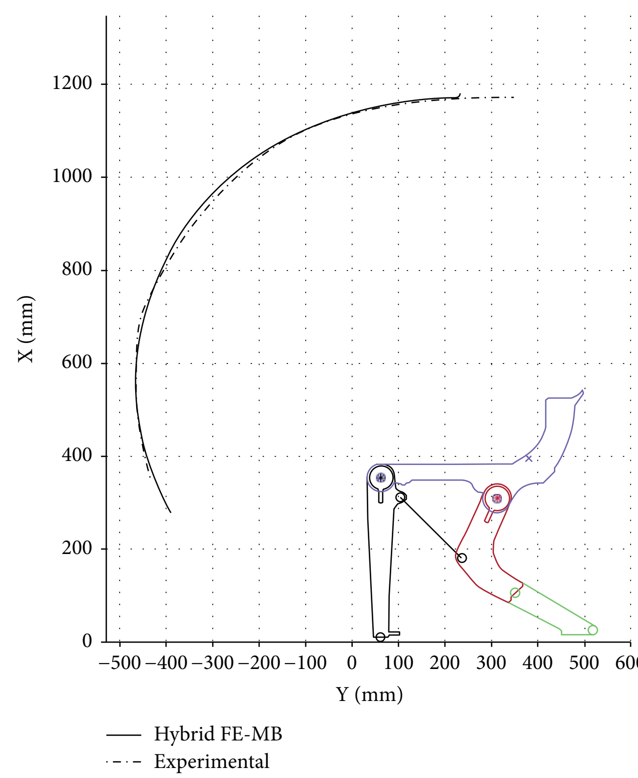

Figure 8: Head path correlation.

It is very important to emphasize that the computational time of the numerical simulations are about 20 hours for the full FE simulation and about 2 hours for the hybrid one.

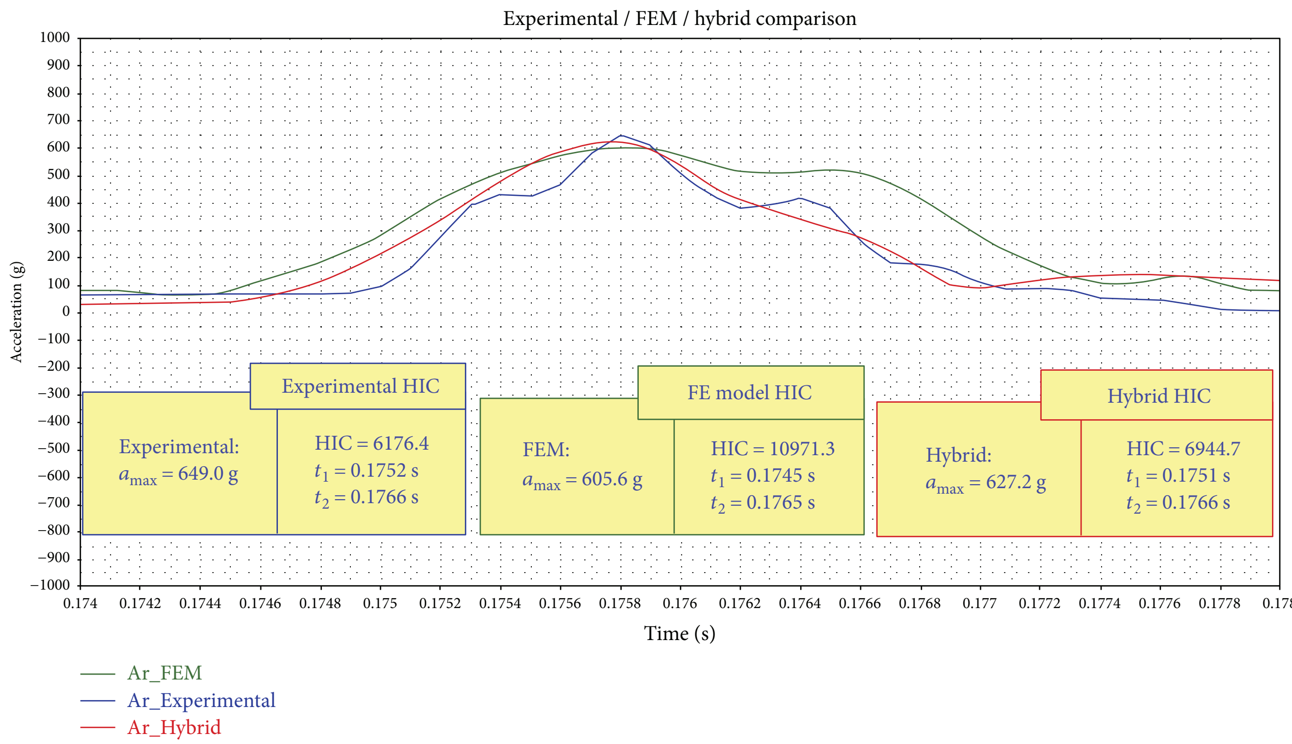

Figure 9: Head resultant accelerations.

4. Conclusions

In this paper, a hybrid FE-MB model has been developed, and its reliability has been assessed against the experimental test results provided by the Geven S.p.A. company and the numerical results carried out by a full FE simulation, presented by the authors in previous papers [22, 23]. The hybrid model allowed simulating the seat sled test, reducing significantly the computational costs with respect to those requested by a full FE strategy and at the same time improving the level of accuracy that can be achieved by a full MB model which does not permit the modelling of the deformability of the seat system. As a result, the hybrid approach is a good solution to exploit both FE accuracy and MB lower computing time.

The performed numerical-experimental result correlation demonstrates the efficiency of the proposed hybrid model in simulating the phenomenon. Moreover, the correlation of the numerical results achieved by the hybrid model with the results carried out by the full FE simulation showed that the former is also able to simulate the kinematics of both seat and dummy during the crash event.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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