A DYNAMIC ANALYSIS STUDY OF AIRCRAFT SEAT CONFIGURATION FOR CRASHWORTHINESS

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Abstract. Every day, around 180,000 commercial flights transport people to all parts of the globe. Although the airplane is one of the safest means of transportation, it is well known that when accidents occur many lives are at risk. Through dynamic simulation, these situations can be computationally modeled to understand the forces, velocities, displacements, and accelerations acting at the plane components/ passenger model and more suitable materials, convenient geometries and seat structures can be tested/ improved to increase passenger's safety. In the present work, a specific guideline is developed in the software LS-DYNA for those who are interested in this type of research. From import/create the aircraft CAD seat geometry, meshing the model, dummy positioning, belt fitting, contact definitions, setting the boundary conditions and model parametrization, to post-processing, a simple example is given showing the step by step procedure to model an aircraft seat with a dummy in emergency landing conditions. The result is to obtain the head injury criterion (HIC) for this example and compare with the ones found in literature, showing the importance of studying passenger's safety and keep improving their survival conditions in emergency landing situations.

Keywords: Aircraft seats, Passenger safety, Dynamic simulation

1 Introduction

Every day, around 180,000 commercial flights transport people to all parts of the globe, Flightradar [1]. According to the International Air Transport Association (IATA), an aircraft has, on average, 90 seats. Considering a passenger load factor of 80%, IATA [2] more than 10 million passengers fly each day. According to Airbus [3] data, the number of flights is increasing every year, but the number of fatal accidents is decreasing. Even decreasing the number of fatal accidents over the years, it is known that when they occur, chances of survival are limited. This is shown by a US National Transportation Safety Board [4] study, where the institution reviewed aircraft accidents in the United States from 1983 to 2000, concluding that 55.6% of aircraft occupants survived the most serious accidents. Of the occupants who died, approximately 60% of fatalities occurred due to impact.

Brownson [5], evaluated the impact on passengers in air crash cases through a correlation between an impact test and a mathematical model, verifying that when they adopt the brace position, passengers have minor damages compared to individuals without the brace position. However, when it comes to airplanes, dynamic tests become very costly and mathematical models are helping to reduce costs with good reliability. For example, Bhonge [6], studied and developed a methodology for cost reduction with dynamic tests on certification of commercial aircraft seats through finite elements in LS-DYNA software and obtained a good correlation between tests and the finite element model.

Olschinka, Riedel, and Schumacher [7] investigated the applicability of the dynamic simulation method with LS-DYNA in-flight passenger seat design as an accompanying development tool in the run-up to certification testing. Aircraft passenger row-to-row seating is required to meet FAR 25-562 [8] emergency landing dynamic conditions, where head impact must not exceed a Head Injury Criterion (HIC) of 1,000 units. The level of HIC is defined by the Eq. (1):

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

Where t_1 is the initial integration time, t_2 is the final integration time, and $a(t)$ is the total acceleration vs. time curve for the head strike, and where (t) is in seconds, and (a) is in units of gravity (g). Chen [9], introduced row-to-row head injury criterion analysis and prediction using LS-DYNA. The seat modeling techniques for the row-to-row simulation were summarized by the author. Mazzotti [10] and Matiello [11] studied the influence of seat pitch in the injury risk probability of passengers through LS-DYNA dynamic simulations. The first observed that smaller seat pitches lead to bigger risks while the second author added vertical accelerations in the analysis and concluded that smaller seat pitches lead to smaller risks to the passengers.

Taylor et al. [12] conducted a series of sled impact tests with two rows of forward-facing passenger seats investigating: seatback type, occupant position (braced and unbraced), the spacing between rows, occupant stature, and interaction with interior walls and concluded that as seat technology has evolved, the most effective brace position has as well, proposing an alternate one. The current position was modified by placing the hands down by the lower legs instead of on the seatback.

The present work has the goal of developing in LS-DYNA software a simple guideline showing the step by step procedure to model an aircraft seat with a dummy in emergency landing conditions. The result is to obtain the HIC for this model varying seat pitch and dummy position and compare it with the ones found in the literature.

2 Modeling and simulation

2.1 Geometry

The seat components were developed based on a seat manufacturer's technical drawings. SolidWorks 2017 from Dassault Systèmes S.A. software was used to reproduce the parts and assembly of the model (Fig. 1). Seat parts including seat legs, cross tubes, seat structure, seat cushions, and seat meal table are elements of the assembly. Simplifications were made so that the geometry received an appropriate mesh in some points, as in-seat foam parts. Despite the challenges in representation and interpretation of some design parts, the main seat dimensions were respected ensuring a high degree of equivalence and maintaining its structural behavior.

Simplifications were also made in the seat to floor fixation since it is beyond the scope of this work to evaluate loading and failure criteria in this region.

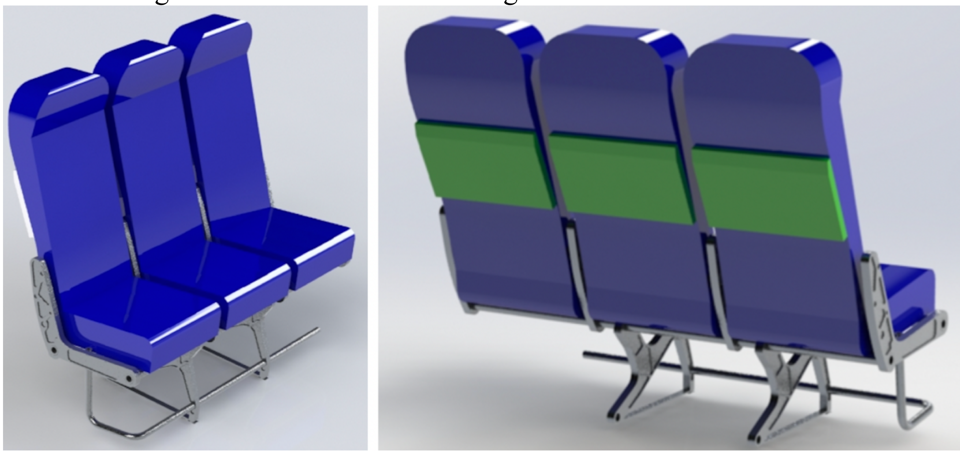

Figure 1. Seat assembly isometric front and rear view

2.2 Materials

Among the materials used in the assembly are Al 7075-T6 and Al 2024-T3 aluminum for the structural parts (gray), compressible foam for the seat (blue) and polymer for the meal table (green). For each material, an elastoplastic model was selected and applied in the finite element software. The software used was the LS-DYNA version R.7.1.1 explicit analysis. The dummy model used in the analysis was the Fast HYBRID III 50th Percentile which accounts for 50% of the world's male population, LSTC [13]. This dummy is 1,75m in height and 78kg in mass. The units used in the dummy are in unit system mm-ms-kg-kg, Guha [14].

Caputo et al. [15] present the stress-strain curve of the foam, material in which the seat cushions are made. In LS-DYNA, material 57 *LOW DENSITY FOAM was used to model the compressible foam of the seats. The seat structure was modeled using LS-DYNA material 24 *PIECEWISE LINEAR PLASTICITY. The stress-strain curve for aluminum (Al 2024, Al 7075) was obtained through static tests by Bhonge [6]. In the LS-DYNA, the material model 89 *PLASTICITY POLYMER was used to model the meal tables. The other mechanical properties data of the materials were taken from manufacturers' catalogs. For simplification, other components with a simpler mesh were modeled as a 20 *RIGID model material because they do not directly interfere in the impact.

2.3 Mesh

The finite element model developed is a combination of solid elements, shell elements and beam elements (Fig. 2). This choice of elements is made based on the cross-section of the component geometry and the criticality level of this component in relation to the model.

In this type of simulation of high decelerations, the shell elements tend to distort causing instability in the model. Thus, solid elements of 8 nodes were selected for simulation in the impact region and were used in the modeling of the frontal seat foam that would receive the impact, in the plastic table and the internal structure to the seat foam. These elements were not used throughout the model because the other parts were not directly in the impact environment. This simplification reduced from approximately 80 hours to 16 hours each simulation run.

The 4 nodes shell elements were used in the complex geometries at the base of the seat and side supports between the seats. They were also used in foams that would not receive the impact.

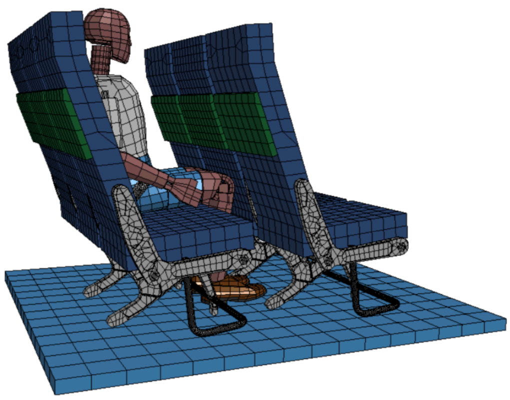

Figure 2. Overview of the parameterized model in LS-DYNA

2.4 Contacts

The model has a total of 84 contacts that include contacts between the seat, seat and floor parts, dummy and seat, dummy and belt, and between the dummy and back of the front seat (where the knee and head impact will occur). All the seat contacts were modeled using *CONTACT AUTOMATIC SURFACE TO SURFACE. This type of contact is recommended for collision simulations since the orientation of the parts relative to one another can`t always be predicted because there are large deformations. For the contact between the center frontal table and center frontal seat, the contact model *TIED NODES TO SURFACE was used to join only the selected nodes on the side of the contact. To represent the contact of the impact seat structure with the seat, the *TIED SURFACE TO SURFACE model was used since the aluminum structure is positioned internally to the foam.

2.5 Boundary Conditions

In the present study, the main interest is the biomechanical evaluation focused on the safety of the passengers, and not structural for seat certification. Therefore, the configuration of test 3 mentioned in Advisory Circular AC25-562-1B [16] was adopted. This configuration has a standard deceleration pulse of 16 g and a peak deceleration in 90 ms [Fig. 3], similar to test 2 for seat certification, but with 2 rows of seats. The floor has no deformation since it escapes the structural evaluation of the seats. The 10-degree yaw angle was also removed excluding the lateral force component to facilitate interpretation of the results. Besides, this simulation setup is similar to most authors who performed tests/ simulations for this purpose, so the results can be compared. Of course, there should be some caveats in the comparison. For example, the seats are not identical, the contacts, materials and boundary conditions adopted by other authors are specific to each model and in many cases are not known, being influence factors that can distort the comparison.

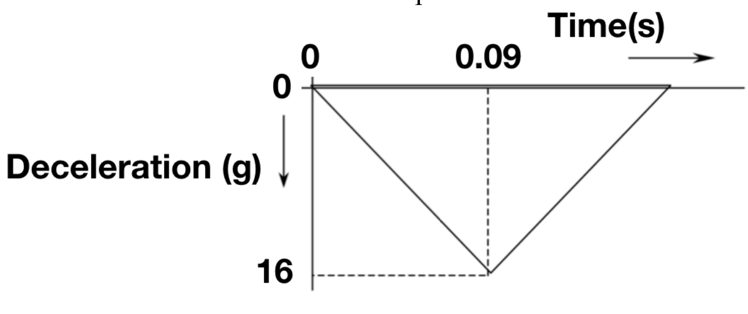

Figure 3. Ideal deceleration pulse for biomechanical

In a collision scenario, the dummy load (acceleration multiplied by mass) is transferred to the structure of the aircraft through the seat belt. The seat structure that sits between the aircraft frame and the seat belts is generally identified as the main loading path. The main load path is connected to the aircraft structure via track attachments, LS-DYNA Aerospace Working Group [17]. Boundary conditions were applied to the floor and seat base structures so that these parts were restricted in all degrees of freedom.

2.6 Dummy position and belt fitting

The LS-PrePost (software used to pre and post-process the model) has a restriction system tool that allows the parameterization of a 3-point belt or a lap belt. For safety belt modeling, a lap belt with 1D safety belt elements and 2D shell elements was parameterized. The materials that used these elements were *MAT SEATBELT and *MAT FABRIC respectively, using data available on the website of Livermore Software Technology Corp, LSTC [18]. The 2D elements belt was used to represent with proper thickness the contact between belt and dummy surfaces.

For parameterization of the chosen belt, a minimum selection of 3 nodes was necessary to determine the positioning area of the belt. The initial node selection was in the aluminum structure lateral to the seat, the second node was on dummy`s abdomen and the third node was in another aluminum structure lateral do the seat (another side).

The initial position of the dummy is another fundamental part of the model. This includes the location of the H-point (or hip point) relative to the seat, the head position, torso, and limbs relative to each other and to the seat. Varying the position of these will also change the HIC values.

The initial position of the dummy was maintained for all pitch distances analyzed so that this initial configuration did not influence the HIC results obtained. The positioning of the dummy in the model followed the specifications presented in section 10 of AC 25.562-1B: Test Preparation, Advisory Circular 25.562-1B [16]. Among these specifications:

1. The ATD (Anthropomorphic Test Device) must be installed in the center of the seat in the most symmetrical position possible. The ATD should be placed on the seat evenly so that the tests have reproducibility.

2. The knees of the ATD must be separated by about 4 inches (101.6 mm).

3. The ATD arms shall be positioned such that they are not over the seat armrests so as not to influence lumbar loads during the test.

4. The feet should be in the proper position for the type of seat tested (straight on the floor for passenger seats). The feet should be placed so that the central lines of the legs are approximately parallel.

Based on the previous assumptions and to investigate the relationship between the dummy and impact loads, four different positions were adopted for the dummy (Fig. 4):

1. Unbraced position and legs backward;
2. Brace position and legs backward;
3. Unbraced position and legs forward;
4. Brace position and legs forward.

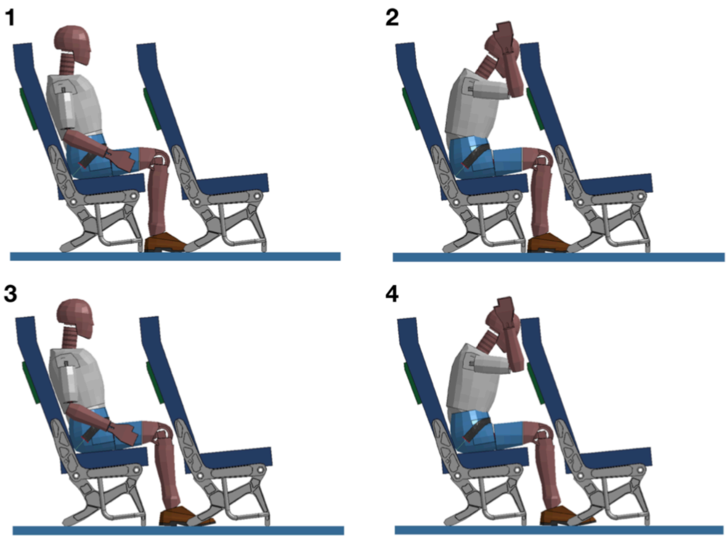

Figure 4. Dummy positions before impact

3 Results

Based on parameterization presented in Chapter 2, it is desired to investigate the distance between the seats that is safer for passengers in emergency landing situations and the position that least causes damage to passengers.

Different settings were selected with pitch distances of 28”, 30”, 32” and 34” based on the minimum and maximum distances recommended by the seat manufacturer. Within these different configurations, the dummy position was varied – braced (B) or unbraced (U) – and legs position was also varied – legs forward (LF) or legs backward (LB) –. The coefficient of friction between feet and floor was 0.5, similar to that presented by Brownson [5].

A total of sixteen simulations were performed considering the standard horizontal deceleration pulse presented in Fig. 3. Dummy`s HIC level was evaluated to identify what is safer for the passengers.

3.1 Head injuries

Through the files generated with the simulation, the head data during the impact were recovered and the head injury criterion HIC 36 was calculated for the different pitch distances with different dummy positions. This index has a maximum time interval of 36 ms and is calculated according to Eq. 1. The results are presented in Fig. 5.

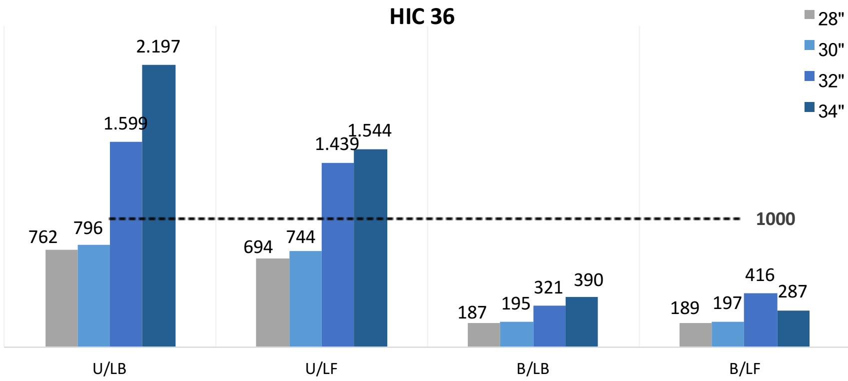

Figure 5. HIC 36 results for the dummy positions and seat distances evaluated

From the graph presented in Figure 5 it is clear that the greater the distance between the seats, the greater the severity index of head injuries. It is noted that from distances of 28” and 30” for distances of 32” and 34” the HIC index increases abruptly. A possible explanation for this difference is because, at the closest distances to the front seat, the dummy hits its knees in the backrest of the front seat before its head does, absorbing part of the impact.

The brace position (Fig. 6) is much safer compared to dummy outside this position (Fig. 7), the criterion of head trauma is 70 to 85% lower in this position. The legs positioning also influences the impact forces. When the legs are set backward, the HIC index is greater in relation to the legs forward.

3.2 Literature data comparison

Brownson [5], checked the HIC index on a sled test using the standard deceleration pulse 16g with a 50th percentile Hybrid III Dummy. The Dummy was positioned in the second row (from the front) in the central seat among the existing 3 in 8 different variations (emergency / non-emergency position, legs forward / legs backward at two different pitch distances, 28” and 32”). Another dummy was placed in the brace position on the seat just in front of the dummy measured in the experiment. The test was randomized to eliminate effects of linear order and each variation was repeated 4 times. All impacts were recorded on high-speed videos. According to the author, HIC indices are higher at a lower pitch distance because of the head impact on the meal table. At a 28” pitch the head impacted with a different (more rigid) meal table area, which has a different energy absorption capacity compared to the area that impacted the dummy at a 32” pitch.

Another point noted by the author is that HIC indices vary with the dummy position. The dummy in the brace position has lower HIC indices. In the unbraced position the dummy is more upright, thus, the head accelerates in a greater distance until the impact with the seat in front of it. This will cause an increase in HIC values since the impact velocity variation is greater. This behavior was the same identified in the present study according to the results obtained.

Taylor et al. [12], affirm that they used a 30.5 inches pitch distance in their tests, one of the narrowest used so far by the major airlines in the United States. This was chosen as one of the worst cases to evaluate the effectiveness of the brace position since, at a nearer pitch, the occupant in the braced position would initially be more upright than if he were in a longer pitch. This position closer to the vertical would allow more space for the occupants to generate differential speed between their head and the back of the seat in front of them, resulting in a greater risk of injury. This closer pitch was also considered a worse case for leg impact since the chance of interaction of the legs with the seat in front was greater. Summarizing, for these authors the smaller the pitch, the more damage passenger suffers.

Chen [9], used the LS-DYNA for two different pitch distances to predict the HIC index in an economy class passenger seat configuration. The author summarized some modeling techniques and compared the results with actual tests. For the author's simulations, the lower the pitch distance, the higher the HIC index. With a 29-inch pitch, the HIC index exceeded 1,000 units and with a 37-inch pitch, the HIC index stood at approximately 840 units. For the real tests presented by Chen [9], the pitch distance of 37 inches presented an average of 846.5 units while for 29 inches the average was 815.5 units, that is, for the real tests the lower the pitch, lower the HIC index. These results are consistent with that found in this paper, but differ from the results found by Taylor et al. [12], Differ from the results found by Brownson [5] and also differ from the results found in the Chen simulations.

Mazzotti [10] and Matiello [11] also used the LS-DYNA to calculate the injury severity in emergency landing cases. The first considered only horizontal accelerations while the second considered vertical accelerations as well. Mazzotti [10] concluded that the smaller the pitch used to space the seats, the greater the likelihood of death in the event of a collision. According to the author, the increase of seat rows in airplanes and, consequently, the decrease of the space between seats tend to increase the severity of the head injury in an accident.

Unlike Mazzotti, Matiello [11], found that the risk of life increases with increasing distance between seats by analyzing the HIC criterion, AIS criterion and limit criterion for forces and moments acting on the neck. The author also noted that very close seats can also increase the risk to passengers.

Table 1 was developed to compare the results of the HIC index found by several authors for different pitch distances. It is known that other factors also influence HIC indexes such as the type of material used in the seats/ front table, initial tension of the belt, dummy position, deceleration pulse applied, coefficient of friction between the dummy feet and the floor, among others. However, in spite of these other factors of influence, there is a direct correlation between pitch distance and HIC indexes that can be better observed in the table below.

Table 1. Different authors HIC index results for horizontal deceleration tests and simulations

Author			Pitch					
	24,8”	25,6”	26,4”	27”	28”	29”	32”	37”
Brownson, 1993. Test					437,50		345,69	
Chen, 2018. Test						815,5		846,5
Chen, 2018. Simulation						1342,5		839,5
Matiello, 2017. Simulation	265,90	288,20	304,80	318,50	337,40	348,6		
Farias, 2019. Simulation					457,725		943,65	
Mean	265,90	288,20	304,80	318,50	410,88	835,53	644,67	843

It was observed in the present study that the lower the distance between the seats, the greater the chances of an interaction between the knees and the front seats, however, the observed was also that in general, the lower the distance between seats, the safer it is for passengers.

4 Conclusions

From the representation of an economy class airplane seats real geometry built in Computer Aided Design (CAD) and transferred to finite element software where the simulation model was constructed, this study verified the safest distance for passengers in landing conditions considering predominantly horizontal loads with addition of gravitational acceleration on the vertical axis. This test configuration was selected because it is recommended in regulation, also, it becomes comparable to most studies developed for this purpose.

Among the configurations available in the seat model evaluated in this paper, 28”, 30”, 32” and 34” pitch distances were selected based on the minimum and maximum distances recommended by the seat manufacturer. Within these different configurations, the dummy position was varied – braced (B) or unbraced (U) – and legs position was also varied – legs forward (LF) or legs backward (LB) –.

The constructed model has mesh simplifications in some regions far from the impact environment and more robust mesh in the pieces that are directly connected to the impact aiming to reduce computational time. This model represented satisfactorily the geometry of the seat and its behavior under impact is coherent with the one found in real situations. Materials of plastic, aluminum, and foam are represented in the zone of impact with elastoplastic behavior, whose modeling was fundamental for energy absorption and approximation of real situation.

It was noted that the more distant the seats are, the more speed the dummy acquires until it reaches the seatback in front of it, that is, in general, greater risks of life exist for passengers with greater distances between seats. There are specific situations where the impact zone may be composed of a more brittle or ductile material, and this also needs to be considered.

It has been proven that the emergency position has a significant difference in an emergency landing and can save lives, generating significantly lower loads on the passengers' head.

The forward leg configuration shows greater advantages over the back leg condition because it creates greater resistance to movement by reducing the dummy's speed. This reduction in speed causes lower HIC indices.

Although the work presented satisfactory results, the limitations of this study are still to adequately represent the internal seat structure as well as the contacts in some regions of the model. Another limitation is to obtain the correct properties of the materials since no real seats were tested.

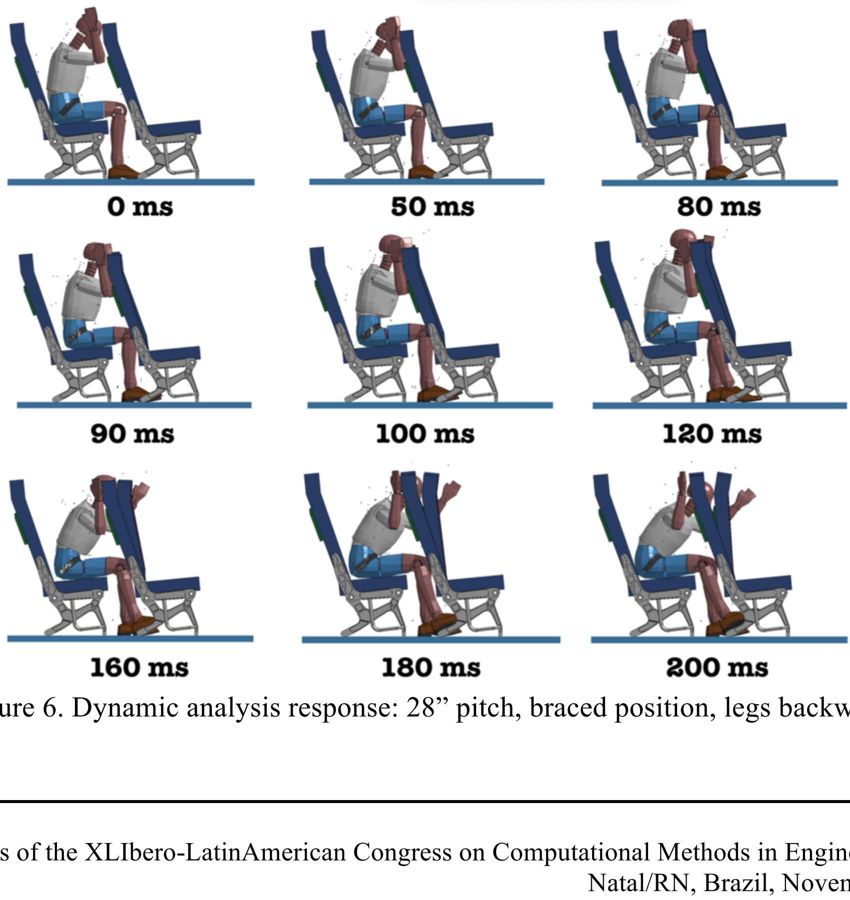

Figure 6. Dynamic analysis response: 28” pitch, braced position, legs backward

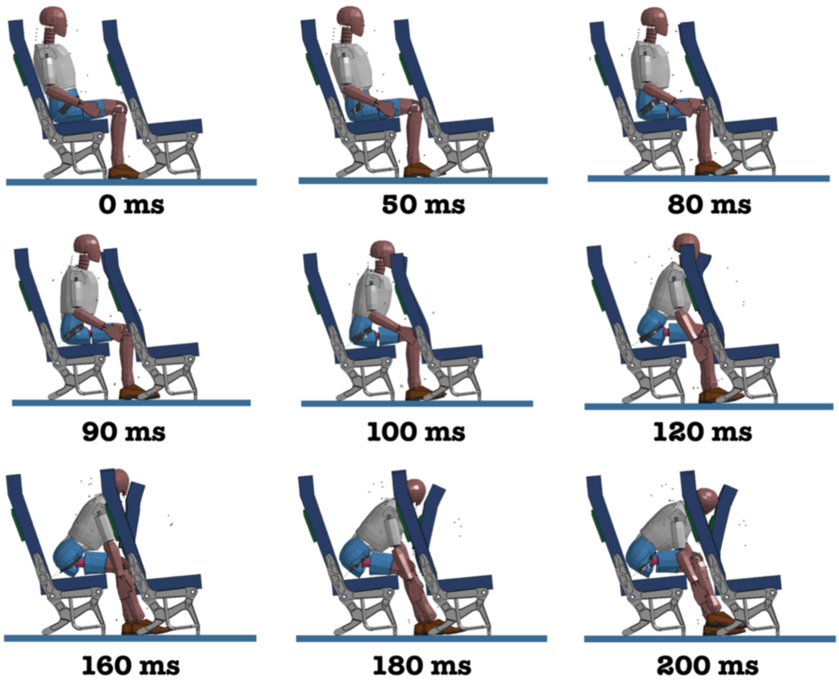

Figure 7. Dynamic analysis response: 28” pitch, unbraced position, legs backward

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