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DYNAMIC FINITE ELEMENT ANALYSIS OF AN AIRCRAFT SEAT

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ABSTRACT

Federal Aviation Administration (FAA) has standards and regulations so as to protect aircraft passengers against some dangerous landing or crash. This paper describes the mechanical strength of a seat and safety of passengers, which is stated in FAR 25.562 dynamic test conditions that contain two cases. Both of them are the longitudinal velocity change dynamic test criteria, one of them has 10^o yaw angle, and the other case has 60^o fixture (floor) angle for the seat. For comparison, zero angle case is also performed in this study. Besides, this paper aims the optimization of aircraft seats which leads to weight reduction in order to design modern economical seat configurations. The optimized seat design must meet the FAR 25.562 criteria. A finite element explicit code, LS - DYNA, is used in order to simulate the scenarios. 50^{th} percentile Hybrid III Anthropomorphic Test Dummy (ATD) was chosen to represent a human body. This paper also includes different seat belt configurations for aircraft. As related to passenger safety, the belt and ATD interaction has critical importance. Head Injury Criterion (HIC) is also significant signs. Furthermore, forces to act in abdomen and torso and then acceleration to act in head, pelvis, abdomen and chest of ATD are shown in the paper. Some kinematic representations of the passenger position are included and their validations are represented. Moreover, the equivalent stresses in aircraft passenger seats made of both isotropic and composite materials are considered in the paper.

INTRODUCTION

Full scale dynamic certification testing of passenger seats is challenging operation. It requires well established test laboratory. It also is very expensive and time consuming process. Using computer aided dynamic finite element techniques instead of traditional tests provide less cost and shorter time. Some engineering problems have simple mathematical models and these are solved exactly with analytical approach. However, some others such as crash or blast are very challenging problems. These have many difficulties and restrains which arise from boundary and initial conditions. In such cases, the numerical methods are used. Due to advances of the computer technology and the numerical simulation codes, obtaining the reliable solutions are easier for such challenging problems.LS-DYNA, MSC-DYTRAN, PAMCRASH, ABAQUS and TNO-MADYMO are, for example, useful finite element codes in order to handle these problems.

Adams, Lankarani and Nick proclaimed that utilization of computer models would have lower cost and would be more effective than the dynamic test of aircraft seats. They tried three different approaches. First, they developed a FE model of the passenger seat for LS-DYNA in order to analyze direct impact effects about a seat. Then, Multi-Body solver, MADYMO, was used with Hybrid II 50^{th} percentile ATD so that kinematic behavior of passengers in crash event is highly important to survive. Finally, for obtaining a high accuracy, both programs were connected to each other, and the analysis was performed. Authors concluded that such computer models are useful and fast tools for crash analysis [Adams, Lankarani and Nick, 2003]. In another study, a seat frame, a restrain system of seat and a rigid body model of 50^{th} percentile Hybrid-II ATD are analyzed by using MSC-DYTRAN [Hermann, Holmes and Hartley, 2001]. Olschinka and Schumacher showed the capacity of dynamic simulations

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for aircraft seats with using LS-DYNA. They worked on old and new seat certification rules and injury criteria. Paper pointed out some differences related to solutions occurred between simulations and tests. Differences are due to pre-stresses and deformations of implicit analyses in dynamic simulations. Paper concludes that LS-DYNA is a reliable simulation code in order to analyze aircraft seat behavior of crash event [Olschinka and Schumacher, 2006]. The FE occupant model FTSS 50 percentile Hybrid II ATD, a seat belt model and a passenger seat structure are used by [Dhloe, 2010].The author validated his results by comparing them with full scale tests. There are many investigations available on the crash analyses in automotive industries. The finite element method is considered as a good choice for crash simulations [MacNaughtan and Khan, 2005]. Also, finite element analysis is used for modeling composite materials. Deka, Vartus and Vaidya investigated progressive damage of a composite laminate. Ballistic limit and energy absorption of composite laminates of various thickness are investigated using LS-DYNA [Deka, Vartus and Vaidya, 2006].

Airworthiness is the measure of suitability of an aircraft for safe flight. Airworthiness certification standards are specified by FAA with certain limits. One of these standards is PART 25: Transport Category Airplanes. FAR 25.562 Emergency landing dynamic conditions define precisely how to perform crashworthiness tests for passenger seat and how to evaluate these results. Passengers must survive after the crash, besides; loss of consciousness should not be occurred. Furthermore, it was noted that a seat structure may yield, however, it must remain attached at all connections after the crash [FAR, 2013]

In this study, the simulation focuses on passengers' safety and aircraft seat structures under FAR 25.562 dynamic test conditions by using LS -DYNA. Pre-investigation shows that it is possible to design a new aircraft seat which will be lighter than old ones and as safe as used ones. Detail investigation will focus on the material optimization of the aircraft seat. The optimization aims to reducing weight of the seat by introducing some alternative composites as seat frame materials.

FORMULATION

Load Cases

FAR 25.562 has two cases of loading [FAR, 2013]:

- Case 1: Airplane longitudinal axis canted downward 30 degrees with respect to horizontal plane; peak floor deceleration must occur in not more than 0.08 seconds after impact and must reach a minimum of 14g.
- Case 2: Airplane's longitudinal axis horizontal and yawed 10 degrees either right or left; peak floor deceleration must occur in not more than 0.09 seconds after impact and must reach a minimum of 16g.

Case 1 aims to find out safety conditions of passengers. Critical indicator for the case is occupant's abdomen load. Case 2 focuses worst case of the seat structure [Dhole, Yadav and Olivares, 2012]. In addition, in order to compare both cases, 0 degree case is performed. This case has 0 degree, and peak deceleration in 0.08 seconds is 16g.

FAR 25.562 dynamic tests have some limitations about forces and HIC values. Such that, occupant HIC should not be exceeded 1000 [FAR, 2013]. HIC of 1000 is equivalent, 18% probability of a severe head injury, a 55% probability of a serious injury and a 90% probability of a moderate head injury, for average adult [Mackay, 2007]. In addition, the maximum compressive load measured between the pelvis and the lumbar column of the ATD does not exceed 6.67 kN. In case of torso restraints are used, tension loads in individual straps do not exceed 7.78 kN [Dhloe, 2010].

Crash Physics

<u>Deceleration Pulses:</u> Acceleration or deceleration during crash events usually define complex functions. Yet, in engineering, some simple general pulses such as rectangular, triangular pulses and their different forms are used in order to represent them. In this study, symmetrical triangular pulse is used. This type of pulse is usually used simulating the crash of structure. Stopping distance and stop time formula of symmetrical triangular pulse and acceleration-velocity-displacement relations are shown in Figure 1, which is adopted from Small Airplane Crashworthiness Design Guide [Labunand Vandenburg, 2012].

$$S = \frac{V_0^2}{a}, \quad t = \frac{2V_0}{a} \tag{1}$$

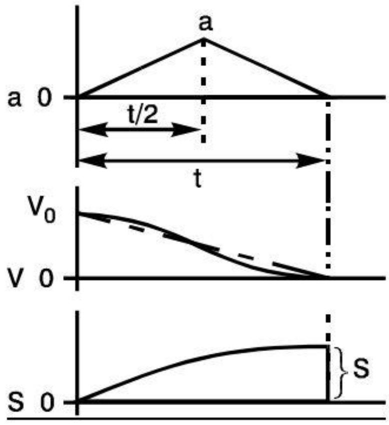


Figure 1: *Acceleration-velocity-displacement relation of the triangular symmetrical pulse*

S: Stopping Distance

V_o: Initial Velocity

a: Acceleration or Deceleration

t: Stop Time

Crash Energy: Simple explanation of this energy, it derives from Newton's Second Law. These equations were retrieved from Small Airplane Crashworthiness Design Guide [Labun and Vandenburg, 2012].

$$F = ma = m\frac{\Delta V}{\Delta t}\bullet\frac{\Delta S}{\Delta S} = mV\bullet\frac{\Delta V}{\Delta S} \tag{2}$$

And, change in the kinetic energy is

$$\Delta KE = \frac{1}{2}mV_2^2 - \frac{1}{2}mV_1^2 \tag{3}$$

where

m: Mass

V_1: Initial Velocity

V_2: Final Velocity

F: Force

Half of square of velocity times mass represents kinetic energy. Change of kinetic energy defines work, and this work is done in crash event.

MODEL

Boundary Conditions and Restraints

FAR 25.562 dynamic test conditions cover two cases, and one additional case is included here for comparison purposes with LS-DYNA. In these three tests, 2 points-seat-belts were used. Three more cases are also added in order to explore 3-points-seat-belt effects for occupant safety. Finally, composite aircraft seat was studied as Case #7 and Case #8. All these tests conditions are summarized in Table 1.

Table 1: Case definitions

Case Number	Angles	Seat Belt Type	Peak Time	Peak Deceleration
Case #1	0 degree	2 points	0.08	16g
Case #2	60 degrees floor angle	2 points	0.08	14g
Case #3	10 degrees yaw angle	2 points	0.09	16g
Case #4	0 degree	3 points	0.08	16g
Case #5	60 degrees floor angle	3 points	0.08	14g
Case #6	10 degrees yaw angle	3 points	0.09	16g
Case #7	60 degrees floor angle	2 points	0.08	14g
Case #8	60 degrees floor angle	3 points	0.08	14g

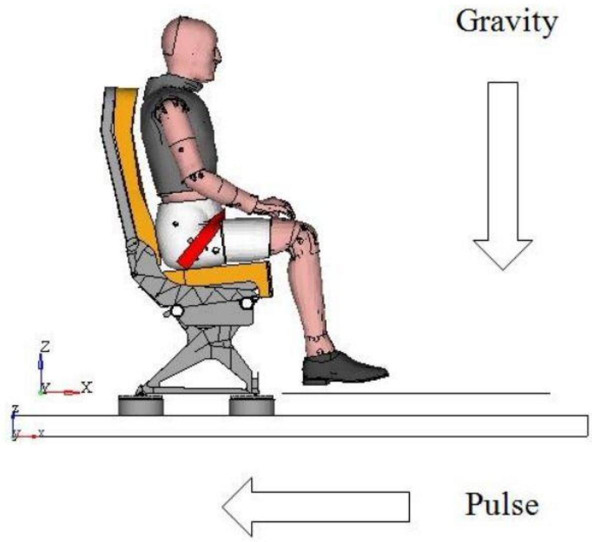


Figure 2: *0 degree and 10 degrees yaw angle tests conditions [Dhloe, 2010].*

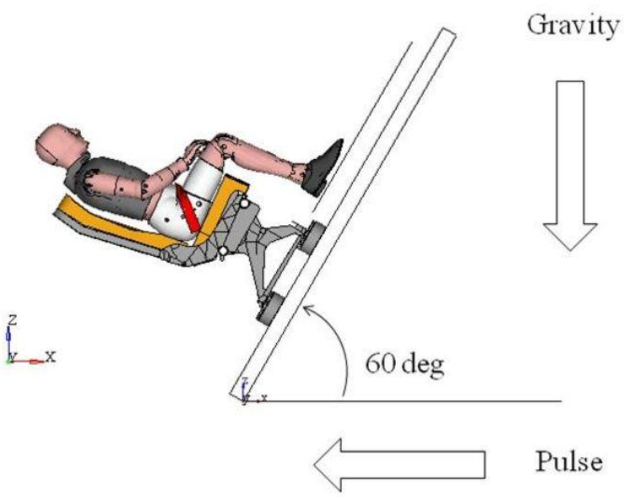


Figure 3: *60 degrees floor angle test condition [Dhloe, 2010].*

Models have rigid plates which are placed between seat and floor. For all these cases, rigid plates fixed in both translational and rotational degrees of freedom with using Ls-PrePost card, Single Point Constraint (SPC). Gravity has applied in all cases. Besides, decelerations are acted to rigid plate again under the above circumstances [Bhonge, 2008].

Material

Structural optimization in terms of weight of the passenger seat frame was planned in this study. Therefore, different materials were used in simulations. As the initial cases, AISI 4340 steel alloy which is frequently used by aviation industry and passenger seats was chosen as seat frame material. Its properties are given in Table 2 [Nuclear Decommissioning Authority (NDA), 2011]. In Case #7 and #8, composite AS4 carbon epoxy is used as seat frame material. Its properties are shown in Table 3 [Thatte, Chandekar, Kelkar, Chalpalkar, 2008].

Table 2: Physical and mechanical properties of AISI 4340 (NDA, 2011)

Name	Equivalent name	Density	Elastic modulus	Poisson Ratio	Tangent modulus	Yield Strength	Elongation at break
AISI 4340	EN24	7,85 g/cc	205000 MPa	0,29	2508 MPa	654 MPa	25,5%

Table 3: Physical and mechanical properties of AS4 Carbon Epoxy
(Thatte, Chandekar, Kelkar, Chalpalkar, 2008)

Property	AS4 Carbon Epoxy
Density (g/cc)	1,60
Elastic modulus E_a (MPa)	125000
Elastic modulus E_b (MPa)	8066
Elastic modulus E_c (MPa)	8066
Shear modulus G_{ab} (MPa)	4129
Shear modulus G_{bc} (MPa)	2420
Shear modulus G_{ca} (MPa)	4129
Poisson Ratio Pr_{ba}	0,0176
Poisson Ratio Pr_{ca}	0,0176
Poisson Ratio Pr_{cb}	0,4657
Shear Strength ab plane (MPa)	90
Longitudinal Tensile Strength (MPa)	1200
Transverse Tensile Strength (MPa)	50
Transverse Compressive Strength (MPa)	900

Finite Element (FE) Model

Meshed geometry, ATD and seat belt positions are shown in Figure 4 and 5 for all cases.

Figure 4-5: *Meshed geometry, dummy and seat belt positions*

NUMERICAL SOLUTION AND DISCUSSION

Kinematic Behaviors of Model and Stress Representations

<u>Case #1</u>

As solutions of case #1, the results of 0 degree case are presented. ATD position at different time frames is shown in Figure 6. At 125 ms, maximum head acceleration, 70 G, occurs. Also, at 90 ms pelvis, chest and abdomen acceleration have a peak. Also, at 90 ms, force to act abdomen reached maximum value.

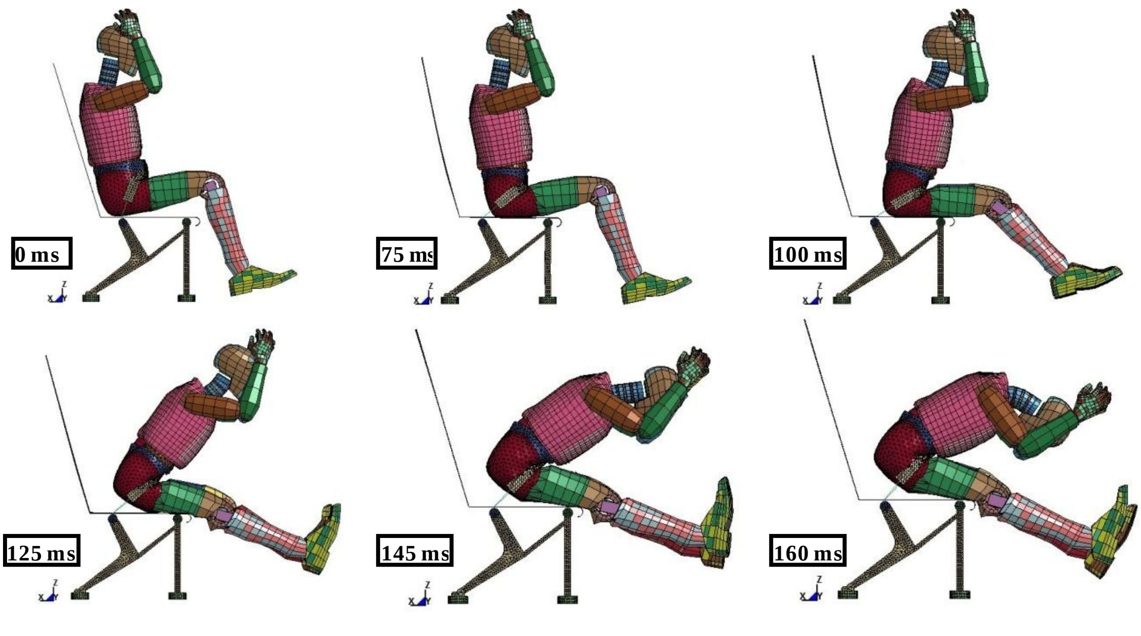


Figure 6: *Kinematic behavior of model in case #1*

In Figure 7, both simulation and the test results at 130 and 160 ms are presented. Seats in test and FE model have similar geometries. The test results were adopted from [Dhloe, 2010].

Test Results **Simulation Results**

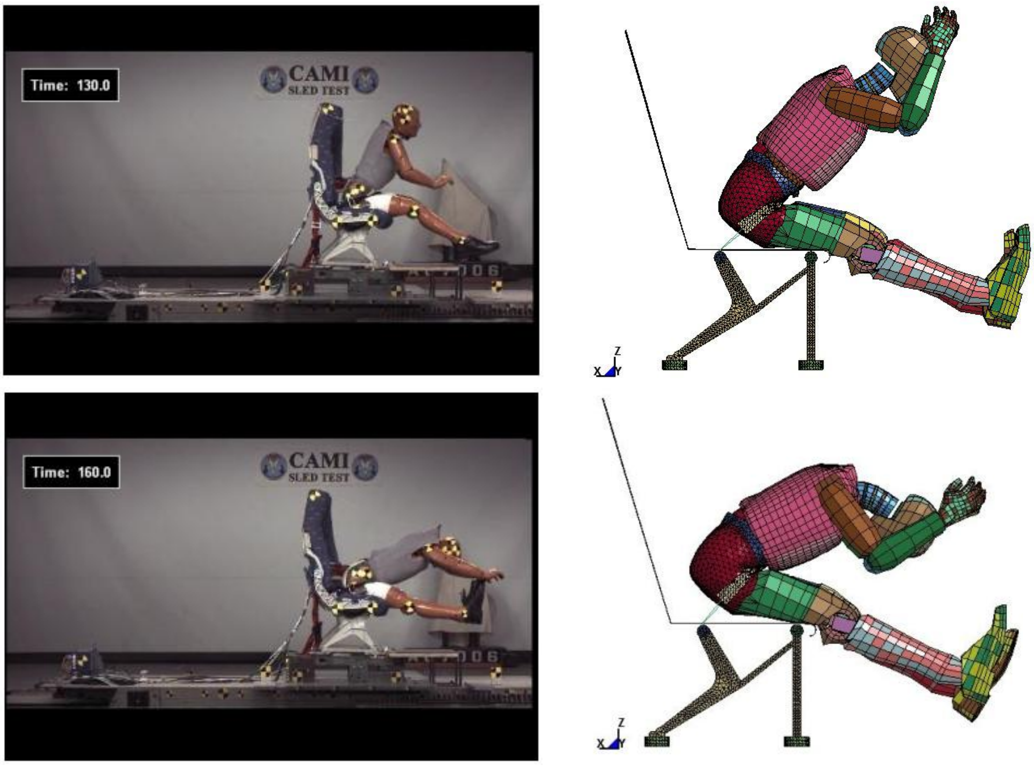


Figure 7: *Comparison for test and simulation results for case #1*

It can be seen that FEA simulation agrees well with the test results for kinematic representations. The distribution of equivalent von Mises stresses at time 125 ms is displayed in Figure 8. It can be seen that maximum von Mises stress reaches 450 MPa. However, AISI 4340 steel alloy has 654 MPa yield strength. Maximum stress value is 1,45 times lower regarding to material limits. In addition, at time 90 ms, maximum stress of 300 MPa occurs at seat pane.

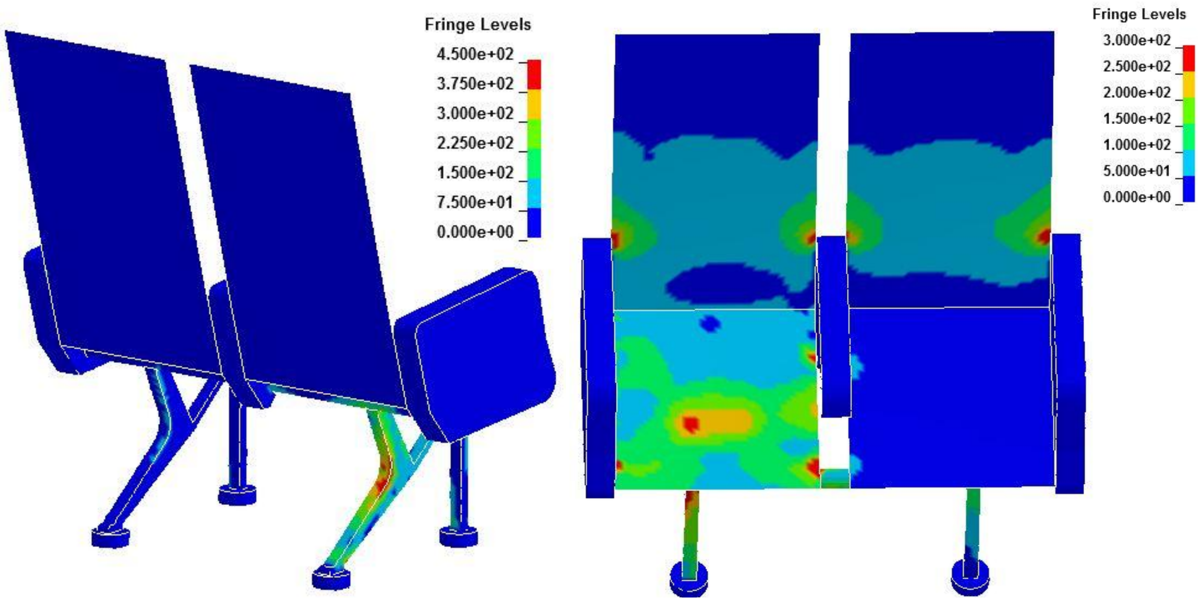


Figure 8:V*on-Mises equivalent stress case #1 at 125 ms and at 90 ms respectively*

Case #2

In case #2, maximum head acceleration occurs at 90 ms and its value is 28 G. Pelvis, abdomen and chest accelerations also force to act abdomen reaches maximum values at 125 ms.

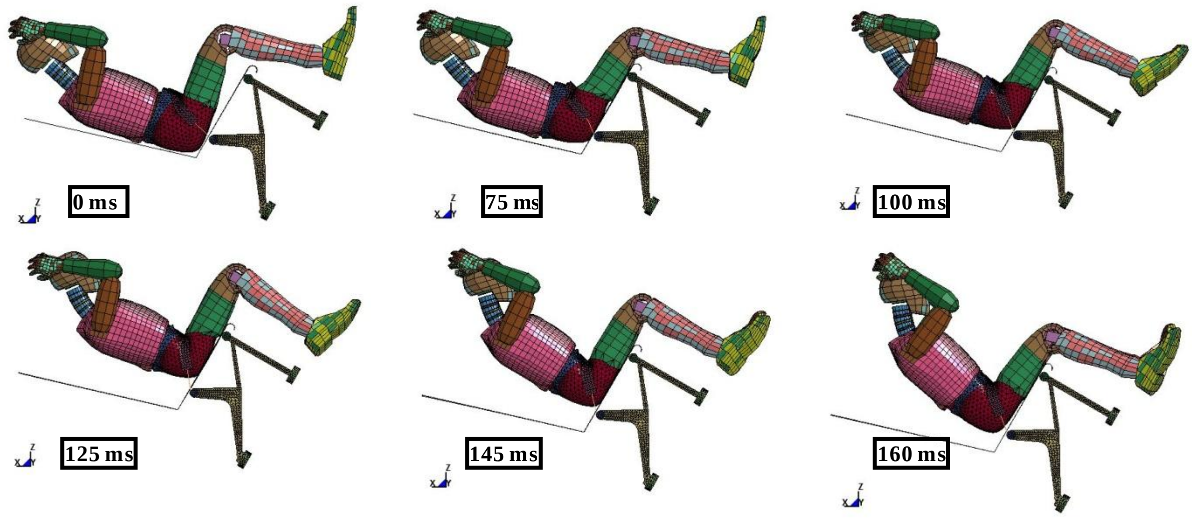


Figure 9: *Kinematic behavior of model in case #2*

Test Results **Simulation Results**

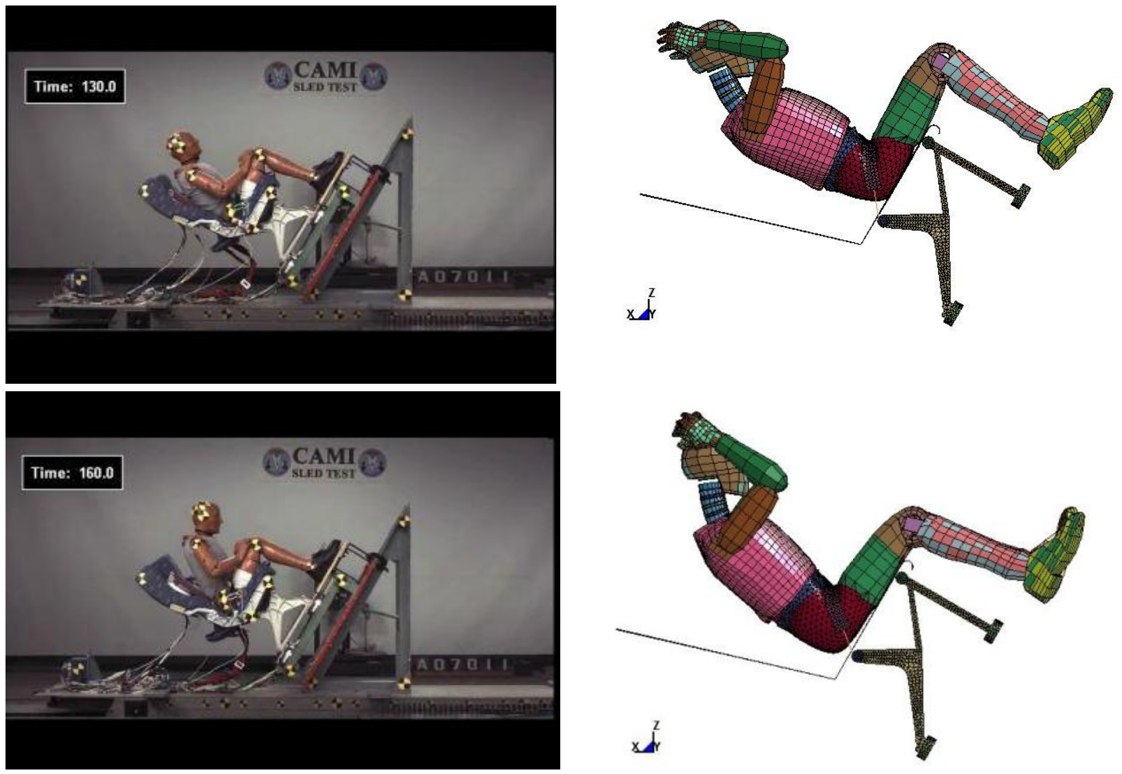


Figure 10: *Comparison for test and simulation results for case #2*

For 60 degree case, test results and simulation solutions are agreed well with each other. It can be seen in figure 11 that the maximum von-Mises equivalent stress of 200 MPa arises at 65 ms. However, the stresses at the seat pane can reach 200 MPa at time125 ms.

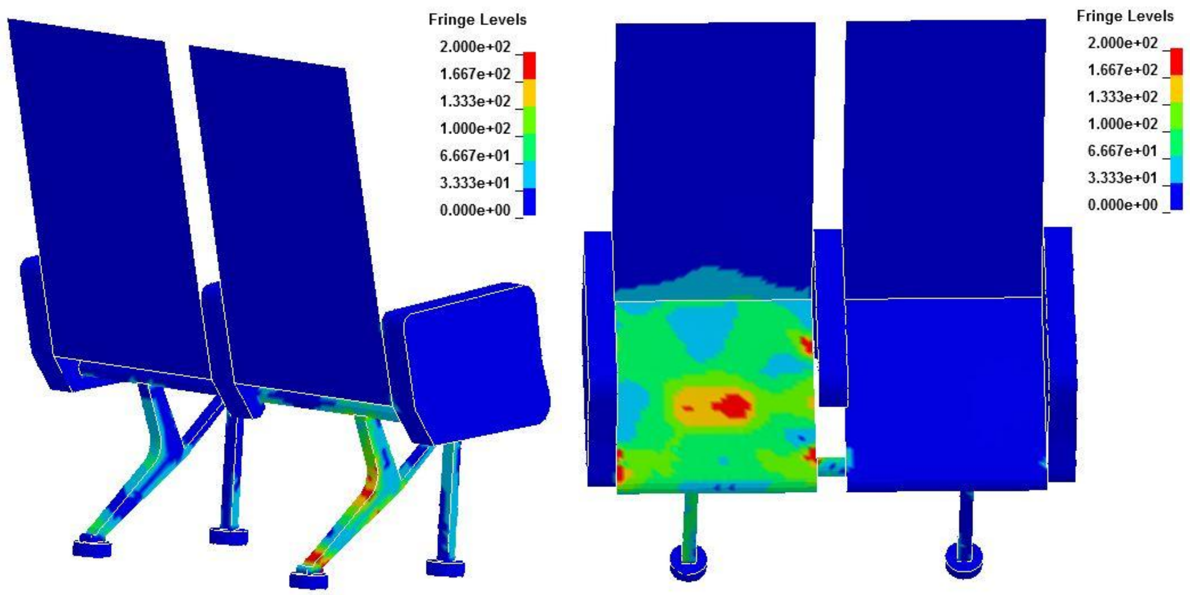


Figure 11 :V*on-Mises equivalent stress for case #2 at 65 ms and at 125 ms, respectively*

Case #3

Head and chest acceleration are reached maximum values at time 122 ms and 135 ms respectively. Besides, maximum pelvis and abdomen acceleration occur at time 90 ms.

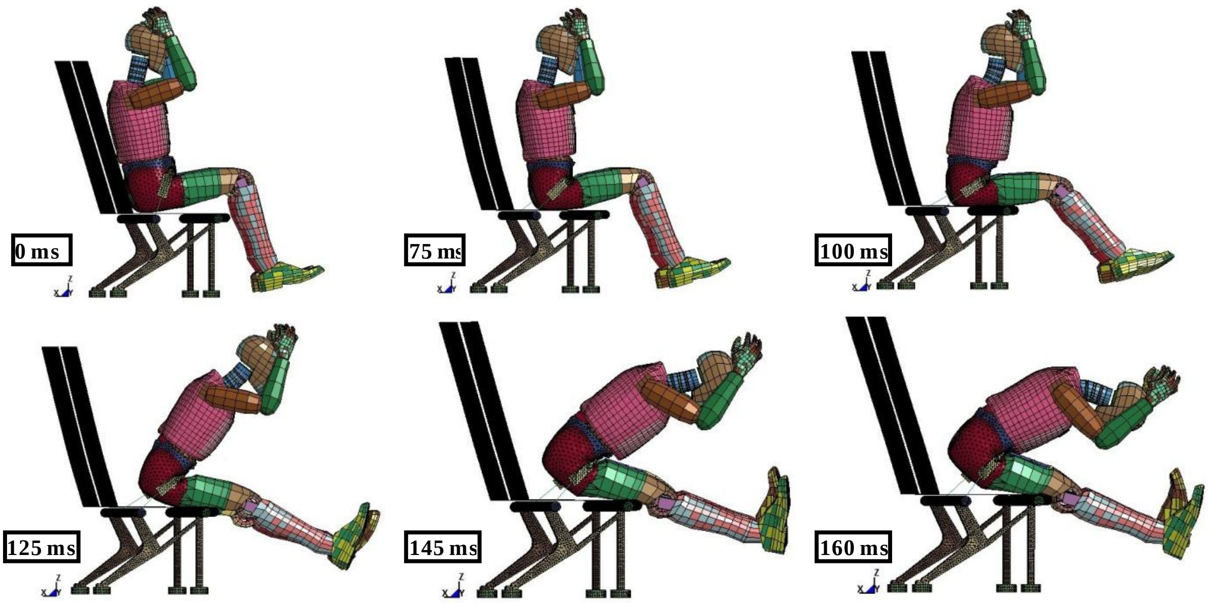


Figure 12: *Kinematic behavior of model in case #3*

Case #3 is the most critical case because all acceleration values reach maximum comparing to other cases. Hence, graph of acceleration values belongs to the case is shown in Graph 1. Not only seat frame but also seat pane von-Mises stresses reached the maximum values at 90 ms. It can be seen from Figure 13 that the seat frame stresses are in the range of 250 - 300 MPa. In addition, the stresses in seat pane are in the range of 350 - 400 MPa.

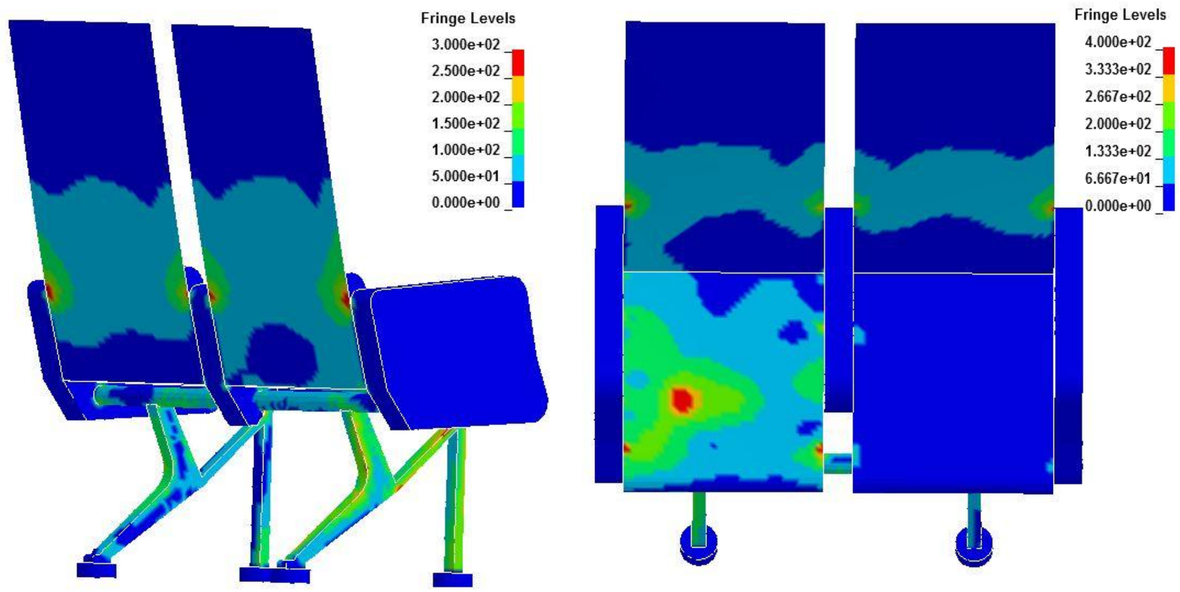
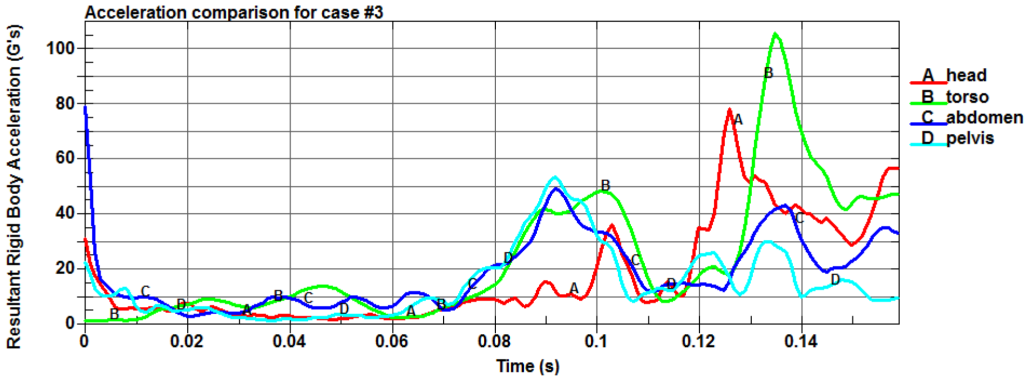


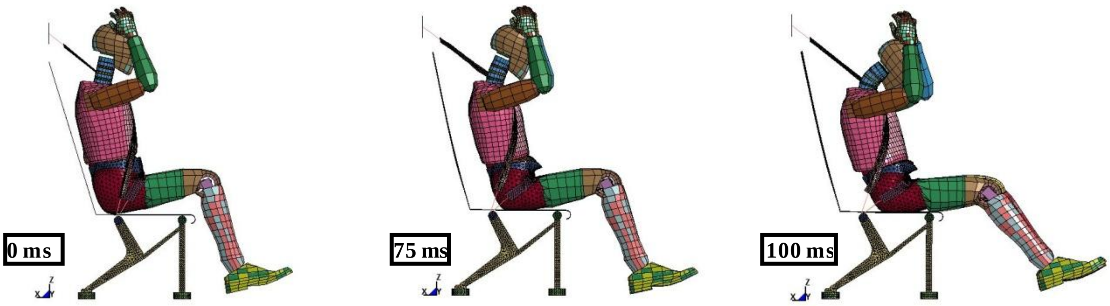
Figure 13: V*on-Mises equivalent stress for case #3 at 90 ms*



Graph 1: Acceleration Representation for Case #3

Case #4

Case 4 is the one of the 3 points seat belt configuration cases. Between at time 90 - 100 ms, head, pelvis, torso and abdomen accelerations reach peak values. Furthermore, maximum forces acted torso and abdomen have peaks at same time interval.



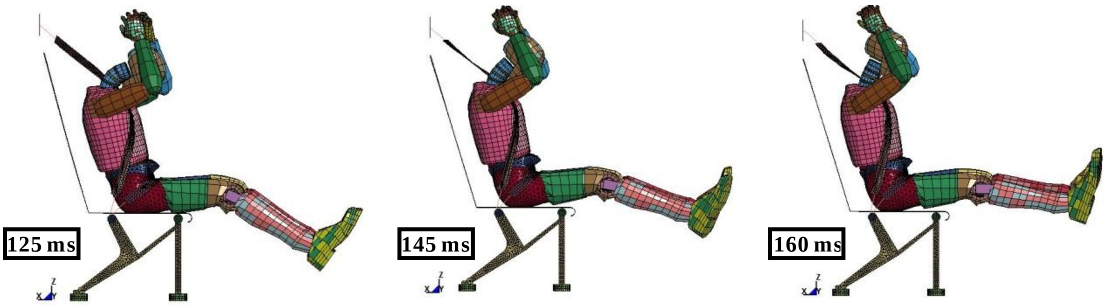


Figure 14: *Kinematic behavior of model in case #4*

Maximum von-Mises stresses occur at time 90 ms in both sections. It was observed 400 MPa at seat frame and 250 MPa at seat pane.

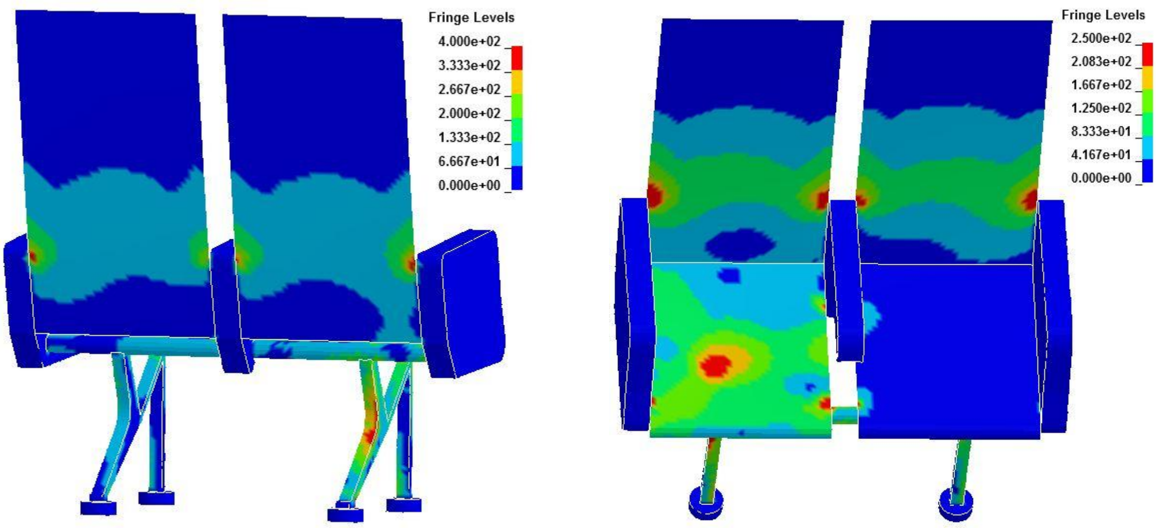


Figure 15: *Von-Mises equivalent stress for case #4 at 90 ms*

Case #5

At time 100 ms, maximum head acceleration, 27 G, occurs. Also, at time 80 ms pelvis, chest and abdomen accelerations reach a peak. It can be seen at time 125 ms, forces on torso and abdomen reach maximum values.

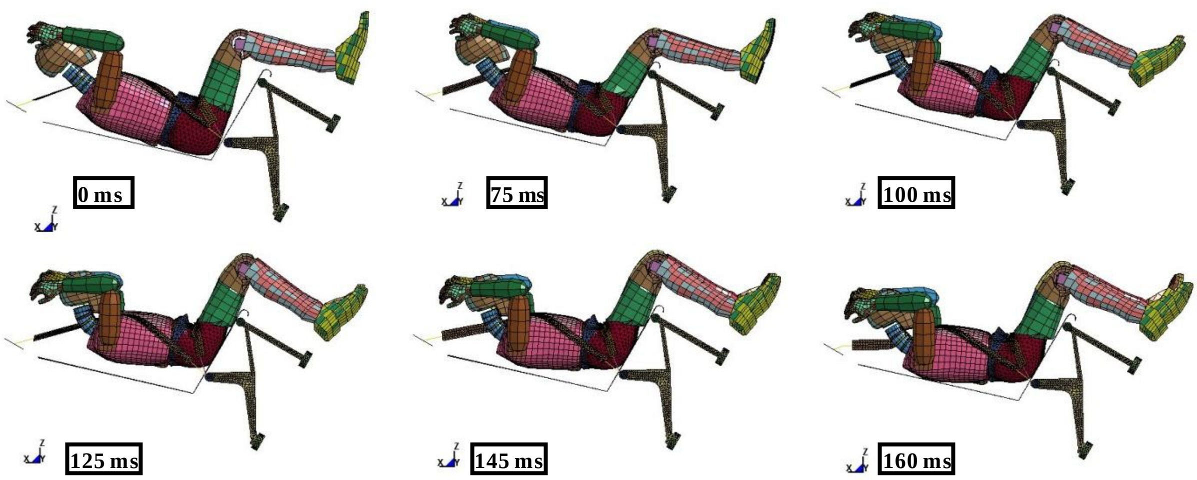


Figure 16: *Kinematic behavior of model in case #5*

The distribution of equivalent von Mises stresses at time 85 and 125 ms are displayed in Figure 17. It can be seen that maximum von Mises stresses reach 150 MPa and 170 MPa respectively.

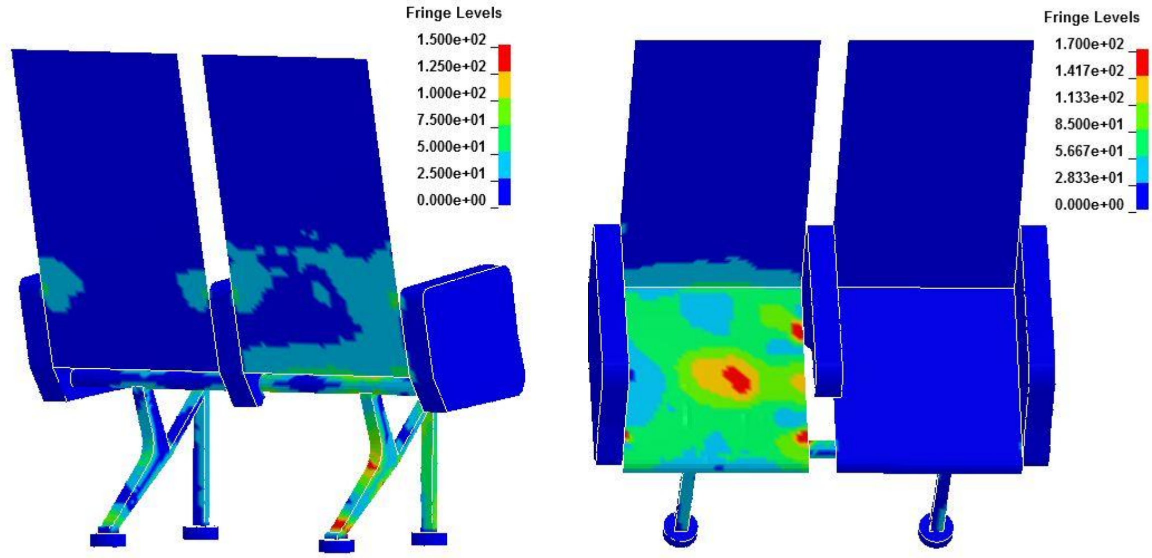


Figure 17: *Von-Mises equivalent stress for case #5 at 85 and 125 ms*

Case 6

Head, chest, pelvis and abdomen acceleration reach maximum values at time 90 ms. Also, forces to act abdomen and torso occur at same time.

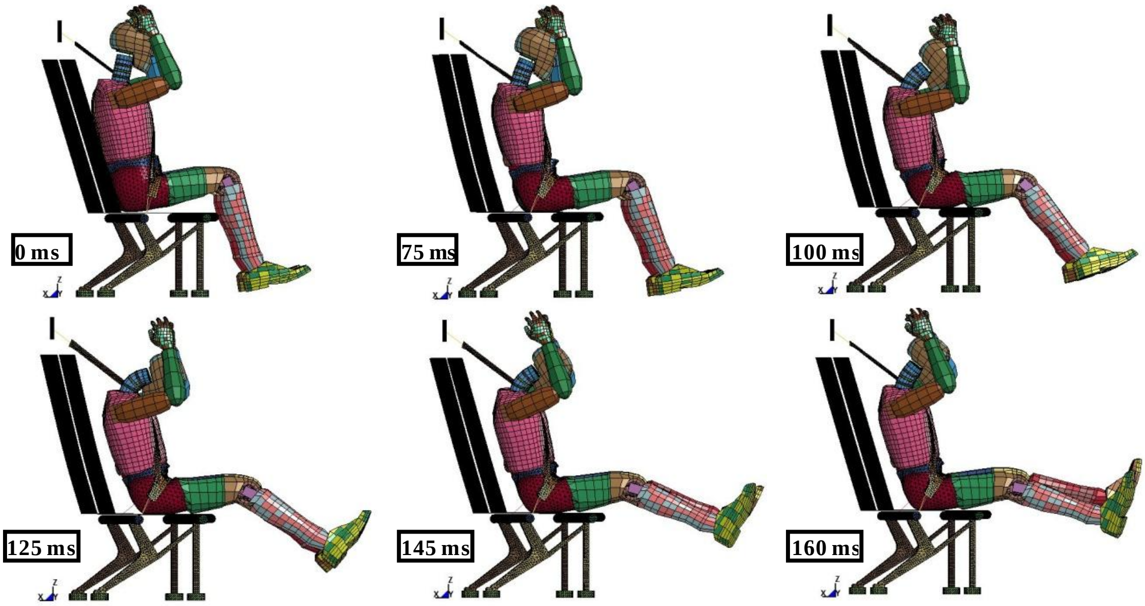


Figure 18: *Kinematic behavior of model in case #6*

It can be seen in Figure 19, seat frame stress is 250 - 300 MPa interval at 100 ms. In addition, seat pane stress occurs between the same interval at 110 ms.

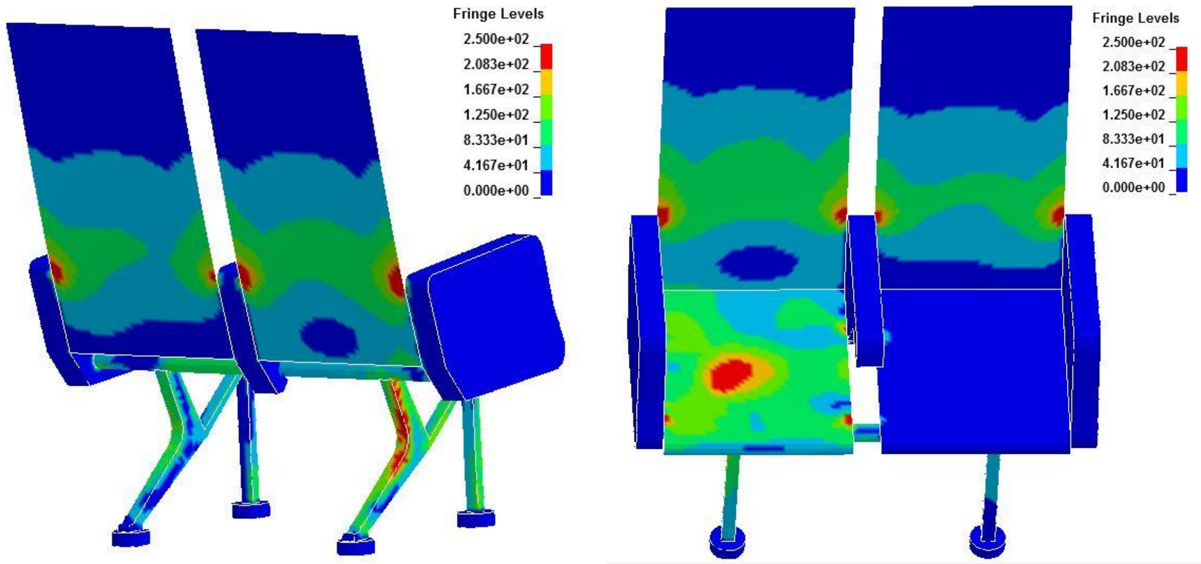


Figure 19: *Von-Mises equivalent stress for case #6 at 100 and 110 ms*

Case #7

Case #7 has same boundary conditions and restraints with Case #2 except seat material. AS4 carbon epoxy is used in case #7 and #8 instead of AISI 4340 steel. The maximum head acceleration of 22 G occurs at time 150 ms. Abdomen has two peak points at 140 and 80 ms. Torso also has two peaks at 60 and 80 ms. Pelvis reaches maximum acceleration 140 ms. Torso at 90 ms and abdomen at 150 ms have the maximum forces.

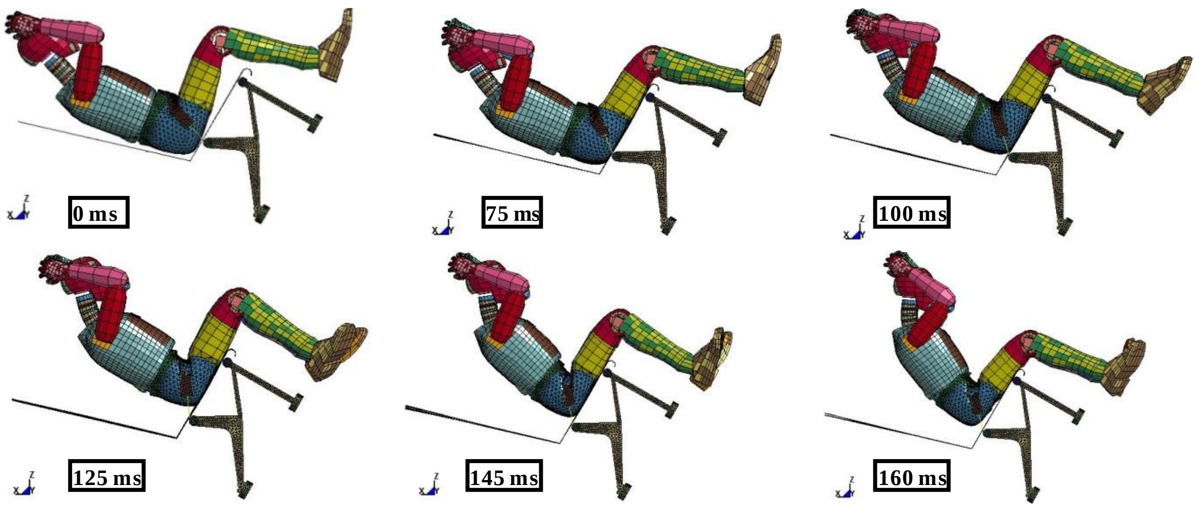


Figure 20: *Kinematic behavior of model in case #7*

In order to investigate failure of seat frames, some criteria have been asserted such as Tsai -Wu, Hashin and Chang-Chang etc. Composite materials can be modeled with different cards in Ls-PrePost. In this paper, MAT22 - Composite Damage card is used for this purpose. MAT22 formulation supports Chang-Chang's theory to examine failure modes. By considering Chang-Chang formulation, if, alpha which is defined shear stress parameter for the theorem, is set to zero, it yields Hashin criterion [Berry, 2011]. Thus, although MAT22 formulation is used in analysis, failure modes are examined according to Hashin theorem. It is checked for all integration points of the case. General representation can be seen in Figure 21. According to LS-DYNA Manual, when fringe level shows less than one, material remains within elastic region [LSTC, 2007].

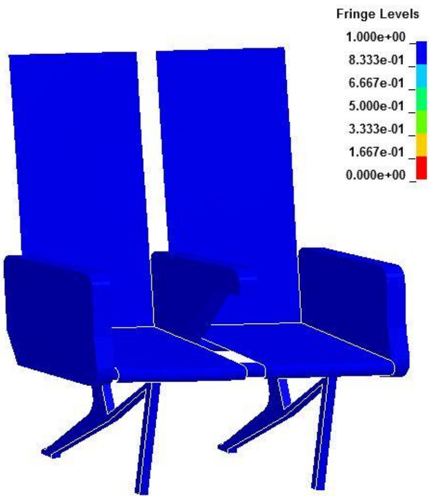


Figure 21: Hashin criterion representation *for case #7*

Case #8

Case #8 and #5 have same test conditions except seat material. As mentioned before, AS4 Carbon Epoxy was used in Case #8. Moreover, head, abdomen, pelvis and torso accelerations reach maximum values at 130, 50, 50 and 60-80 ms respectively. It can be seen at time 150 and 100 ms, forces on abdomen and torso reach maximum values.

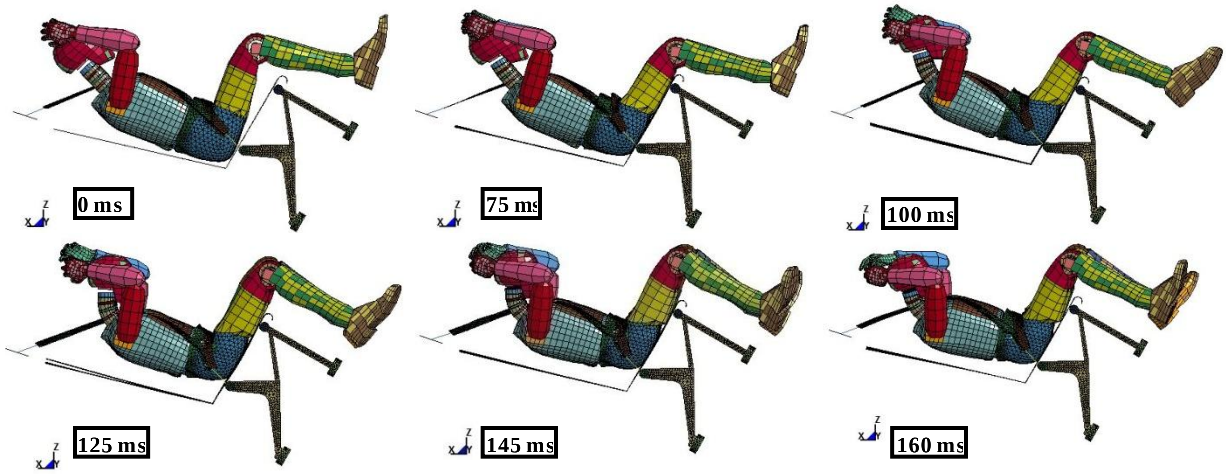


Figure 22: *Kinematic behavior of model in case #8*

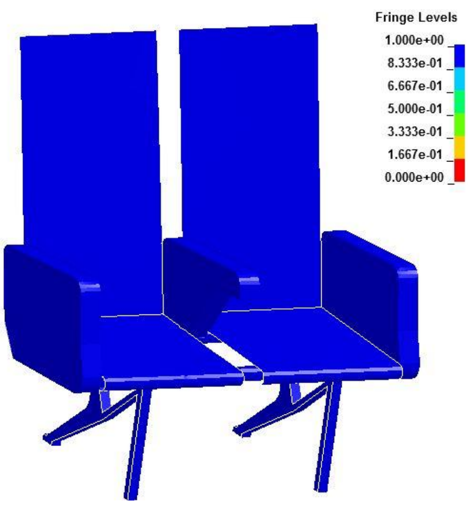


Figure 23: Hashin criterion representation *for case #8*

As noted that, it is assumed in all these scenariosthat seat belts are not ruptured. A seat belt test is detailed process. It should be modeled with D-ring, retractor and fabric together. Besides, dynamic overturning may be taken to account. Some detailed explanations may be found in [Pedrazzi, Elsäßer, Schaub, n.d].

As can be seen in figures above, for the first 6 cases, von - Mises stresses are lower than the yield strength of AISI 4340 steel. This clearly demonstrates that the material of the seat has remained in elastic region. This deduction encourages us to design a new lighter seat. Hence, composite frames may be used for this goal. As shown in figures 21 and 23, new seat as safer as old one in terms of strength. Forces and HIC values about passenger's safety should be reviewed in order to make a final decision.

Occupant Safety Indicators

The occupant body accelerations, forces and HIC values are given in Table 4 - 5 and 6, respectively .

Table 4: Accelerations on the occupant's head, pelvis, abdomen and torso

Case Number	Maximum Accelerations			
	Head (G)	Pelvis (G)	Abdomen (G)	Torso (G)
Case #1	69,11	60,32	49,33	63,41
Case #2	27,51	33,21	33,16	34,28
Case #3	78,00	56,89	48,76	108,77
Case #4	44,32	43,38	47,78	38,58
Case #5	26,96	26,76	47,52	27,56
Case #6	38,02	32,97	51,04	37,72
Case #7	22,76	30,46	39,54	39,63
Case #8	34,69	33,75	29,50	35,53

Table 5: Forces on the occupant's abdomen and torso

Case Number	Maximum forces act on abdomen (kN)	Maximum allowable force for abdomen (kN)	Maximum force act on torso (kN)	Maximum allowable forces for torso (kN)
Case #1	1,67	6,67	2,17	7,78
Case #2	1,54		0,31	
Case #3	1,45		1,50	
Case #4	2,68		5,29	
Case #5	2,23		2,41	
Case #6	2,73		4,41	
Case #7	3,59		0,03	
Case #8	1,24		3,23	

Table 6: HIC values for all cases

Case Number	HIC values	Maximum allowable HIC values
Case #1	451	1000
Case #2	177	
Case #3	415	
Case #4	238	
Case #5	184	
Case #6	228	
Case #7	179	
Case #8	210	

As an initial interpretation, it can be easily said that HIC and force values in all cases are less than specified by the FAR 25.562 dynamic test standard values. However, there are not restraints about acceleration values for occupant in the standard. Thus, it may be stated that less accelerations is the best options.

As mentioned before, Case #1 is not included in the standard. The only aim for this case is comparison. The case has higher acceleration values and also highest HIC value. In case #2, there is an angle between floor and seat. The angle do not allow occupant to accelerate dramatically. Hence, all maximum acceleration values in case #2 are lower than the other cases. Also, it has the lowest HIC value. Another high acceleration values, which are arisen from 10^{o} yaw angle, can be seen in case #3. Especially, head and torso which are not fastened parts of the body, have maximum acceleration values considering the other parts of ATD. Also, HIC value is high to compare with other cases. In view of this information, it is clearly seen that an aircraft which will be made emergency landing, if possible, should be had pitch angle between ground and its body. In this situation, possibility of injury for occupants is reduced. If, it lands in parallel with the ground or lands with yaw angle, possibility of torso and head injury increased.

It can be claimed that case #4 has lower acceleration values respect to case #1. 3 points seat belt is beneficial for the occupant safety. Thanks to this type of seat belt, maximum acceleration values at all parts of occupant are reduced. Especially, at the torso of passenger has 40% lower acceleration. HIC value at this case is almost half of the HIC value at case #1. If, case #5 and #2 compared, all these data show that there are not dramatic differences between both cases. Because of seat position, second seat belt do not affected to ATD. It is obvious that there are large scale differences between case #6 and case #3. Acceleration at the torso of ATD is decreased 66%. Moreover, maximum head acceleration in the case #6 is half of the case #3. Also HIC value is reduced from 415 to 218. 3 points seat belt works well for the case.

Abdomen is the most vulnerable part of human body for this type of crash. It is covered by 2 points seat belt and forces affects directly its. In cases which contain 2 points belts, forces to act ATD's abdomen remain constant approximately. However, after the using 3 points belts, they increase by a small amount. These types of seat belt which are fastened near the abdomen area, create more stiff region. Taking all these cases into consideration, it is claimed that although, maximum force acts on abdomen is 2,73 kN in case #6, it is 2,45 times lower than allowable limit.

Torso accelerations are reduced dramatically by using 3 points seat belts in all cases. Unlike the acceleration values, forces have been increased. When second belts disallow ATD's torso to accelerate, chest regions have been exposed to compression. The worst case is case #4 which has 5,29 kN force for torso. It is the 1,5 times lower than the stated in standard.

If it is considered head and pelvis conditions, maximum acceleration values about them decrease with using 3 points belt. As stated above, HIC is the most reliable indicator in order to realize passengers safety. Especially for case #1 and #3, HIC values have shown serious declines.

In light of all these facts, using 3 points seat belt is a good idea for safety in emergency landing conditions. Case #2 may not be need for this type of precaution. Yet, all other cases have more rough conditions for human safety. 2 points seat belt system provides adequate safety in problem-free flight. As a recommendation, it can be designed a new belt system for aircrafts which contains second seat belt in case of only emergency landing conditions.

It is clearly mentioned that accelerations and forces which is obtained from case #7 and #8, have stayed below the limits in FAR 25.562 dynamic test conditions. They have low HIC values. Besides, they are also compatible with case #2 and #5. Not only stress representations, but also these results are shown us there will be no obstacles in the future in order to create lighter and safer aircraft seats. All studies may be just considered pre-investigation for this purpose.

Old design seat which was used in first six cases has 74 kg weight. As seen in any figures, the seat provides seating for 2 people, so one seat has 37 kg weight. For the new seat, weight value is decreased from 74 kg to 23,58 kg. It can be said that the new one seat has 11,79 kg weight. As a conclusion, the new seat is lighter 3,13 times than the old design which corresponds that the first design lost 69% of its weight. It should be noted that lighter seat can brings huge amount of fuel saving.

CONCLUSION

Important conclusions made from this study are summarized below.

- An explicit code LS-DYNA is a good choice so as to develop FE model of typical aircraft seats.
- FEM may be used reliably in order to simulate FAA standards and regulations.
- 50th percentile Hybrid III ATD which is a detailed FE model, represents human body properly.
- Different seat belt configurations are good options for safer flight.
- Computer simulations can really be helpful in product development process.
- Composite materials are good options in order to use in aircraft seats.
- Composite materials provide some advantages such as weight reduction and fuel consumption.

Future Recommendations

- Aircraft seat which contain cushion layer will be simulated.
- Front seat can be included scenarios in order to determine proper seat distance.
- FEA simulations which contain carbon epoxy material, may be performed for other cases.
- Different materials can be experienced for lighter seat, besides geometrical optimization may be performed in order to provide safer flight and lighter seat.
- Simulations can be redone with finer mesh sizes.

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