THE FOURTH TRIENNIAL INTERNATIONAL AIRCRAFT FIRE AND CABIN SAFETY RESEARCH CONFERENCE
NOVEMBER 15-18, 2004

DESIGN OPTIMISATION AND EVALUATION OF A THREE-POINT HARNESS SEAT DESIGN FOR AIRBUS A320 AIRCRAFT FAMILY

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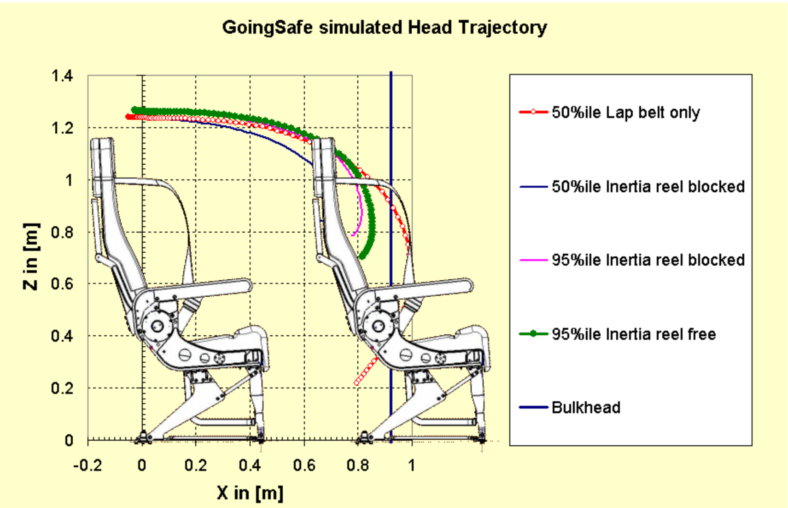
Keywords:
Aircraft seat, Aircraft crash, Three-point harness, MADYMO, Simulation.

Abstract

The DYNASAFE RTD project demonstrated the feasibility of a 3-point shoulder harness for enhanced occupant safety in commercial aircraft in compliance with FAR/JAR 25.562. The GOING-SAFE project was started to implement the advanced safety concept in an interior design, compatible with the passenger's comfort and the airline commercial and technical requirements. The Airbus A320 family was selected for the design implementation.

This paper describes the crash simulations of this seat design occupied with different passenger sizes, using MADYMO multi-body and finite element techniques. These simulations are capable of providing directions for design improvements in an early stage of the design process by means of parametric studies and optimisation. Furthermore an accurate prediction of the occupant kinematics and injury risk as well as seat and floor reaction loads is given, even before the first seat prototype is built. In this way the feasibility of a solution for the 16G FAR/JAR requirements is demonstrated and a wide range of seat occupation, passenger sizes and cabin layout configurations are evaluated. This approach pledges a cost efficient and first-time-right design process that complies with critical time-to-market conditions.

In this effort TNO Automotive Safety teamed up with the design & engineering firm Structural Design & Analysis (SD&A) in Brussels, Belgium and the seat manufacturer AvioInteriors in Latina, Italy, in a consortium sponsored by the European Commission.



INTRODUCTION

Most accidents with aircraft are minor and cause no significant risk to the aeroplane or its occupants. Some, however, can result in major injuries or fatalities. Studies of serious accidents have shown that the occupants and their seats can be exposed to a substantial deceleration pulse. New 16G-performance standards for passenger aircraft seats were set forth in June 1988 by the U.S. Federal Aviation Administration (FAA), followed by the European Joint Aviation Authorities (JAA), to improve the chances of passengers survival in take off and landing crashes (FAR/JAR 25.561/562 [1]). Together with AvioInteriors, one of the biggest aircraft seat manufacturers in Europe and the design and engineering firm SD&A, TNO Automotive Safety has engineered a new seat configuration that improves the occupant safety beyond that of the regulatory requirements.

The European Commission (EC) RTD-Project DYNASAFE [2] demonstrated that the proper use of shoulder harnesses, in addition to the conventional lap belt, would reduce major injuries and fatalities and proved the compatibility of the concept with the structural limitations of current aircraft floors.

As a follow-up the EC-project GOING-SAFE addresses the technical and human factors involved in the implementation of 3-point shoulder harnesses, on all seats, in passenger's aircraft. The resulting hardware should be compatible with the passenger's comfort and the airline commercial and technical requirements. The new designed interior must be suitable for application in a member of a large aircraft family to enable the collection of passenger's criticism and the airline's appreciation. This information should provide sufficient evidence of feasibility in the areas explored, to enable the Air Transport Industry and the Regulatory Authorities to take substantiated decisions. The aircraft family selected for the GOING-SAFE development is the Airbus A320 family.

The TNO Automotive Safety work presented in this paper deals with early stage design issues solved with parameter studies and summarises the occupant safety performance assessment of the concept. The effectiveness of a three-point belt system is studied and whether the seat and existing floor structure will sustain the forces that a three-point belt system exerts in crash conditions. A wide range of occupant sizes, seat occupation and cabin layout configurations is explored in the simulation matrix. MADYMO [3] is used as a simulation tool to predict injury values and structural force levels. The MADYMO multi-body and finite element solver package has got a proven track record in the field of crash safety.

GOING-SAFE concept characteristics

The design characteristics of the GOING-SAFE concept are in line with those tested in DYNASAFE [2]. Each seat is equipped with a 3-point shoulder harness (3-PSH) as show in . The shoulder belt is stored on an inertia reel in the backrest of the seat when it is not used. After fastening the lap belt the shoulder belt can be fastened and unfastened in an extra buckle. The inertia reel provides the comfort of free movement of the occupant upper torso in normal operational conditions. In crash conditions however the inertia reel must block the shoulder belt to offer the occupant a safe response to the crash deceleration. To reduce the loads on the shoulder belt, backrest, seat structure and cabin floor, the backrest hinge is equipped with a energy absorbing device. The load path from the shoulder belt inertia reel through the seat leads to the necessity of considerable seat structure reinforcements.

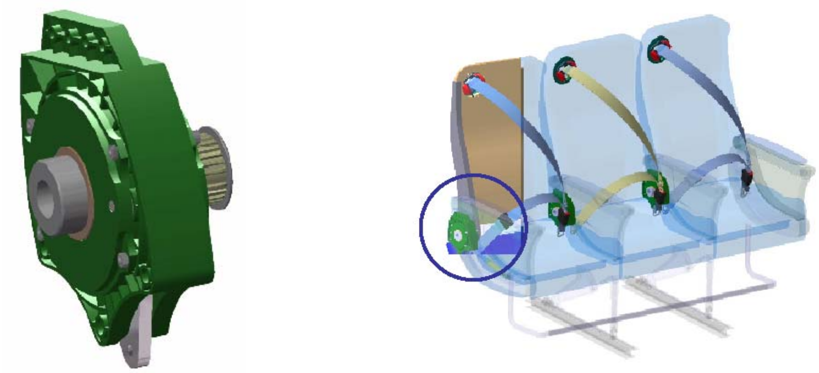


Figure 1: DiscoLock design (Patent pending see http://www.aeroseatingsafe.com)

Model development

Seat and cabin layout model set-up

The MADYMO model that TNO Automotive developed for DYNASAFE [2] is used to conduct a model validation exercise based on dynamic seat tests. The DYNASAFE design was tested in three cabin configurations according to FAR/JAR 25.561/562 [1] required crash conditions using the Hybrid II crash dummy:

- Vertical pulse, 14G on time base 160ms, Downward 60 degrees, Yaw 0 degrees.
- Horizontal pulse, Bulkhead in front, 16G on time base180ms, Yaw 10 degrees
- Horizontal pulse, Row to row, 16G on time base180ms, Yaw 10 degrees

The tests with the vertical pulse and the horizontal pulse with the bulkhead in front allow validation of the model with respect to the dummy kinematics and dummy-seat interaction (see Figure 2). The model validation with regards to interaction of the dummy head with the front seat is done with data of the horizontal row to row test.

Figure 2: MADYMO model versus horizontal 16G bulkhead test kinematical correlation (Left: Time: 0ms, Middle: Time 100ms, Right: Time 160ms)

With the validated DYNASAFE model, parameter and optimisation studies are performed to solve GOING-SAFE design issues. After the freeze of the GOING-SAFE A320 interior design the MADYMO model was updated to represent the final configurations in all variants. The variants considered are (triple seat unless otherwise stated):

- Standard seat row with bulkhead in front
- Standard seat row with seat row in front (pitch 34”, 32” and 30”)
- Emergency exit seat row (9 degrees pre-recline, standard 12 degrees)
- Narrow seat row
- Extra narrow seat row
- Dual seat row (no aisle seat)

This set of models was used to evaluate the compliance with the airworthiness requirements according FAR/JAR 25.561/562 [1] and broader aspects on cabin safety and floor loads for a range of occupant sizes and seat row occupation. For reference purposes some lap belt only simulations are performed.

Dummy model scaling

To enable the design performance assessment for a range of occupant sizes the MADYMO Hybrid II dummy model (50 percentile male) [3] was scaled up and down to represent the 95%ile male and 5%ile female occupant size using advanced techniques. In Figure 3 the Hybrid II dummy models developed by scaling are shown.

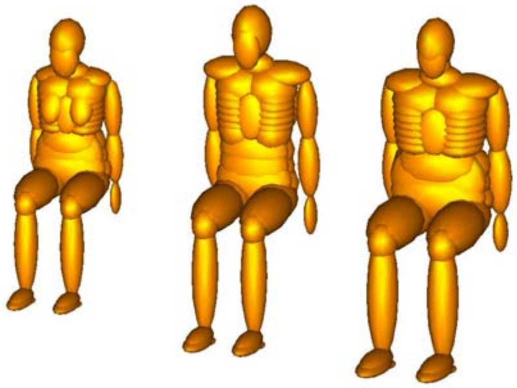


Figure 3: Hybrid II dummy scaled models. Left: Small female (5%ile), Middle: Average male (50%ile, base for scaling), Right: Large male (95%ile)

Different scaling factors are specified for x, y, and z dimensions. Furthermore, different scaling factors are applied for different body parts, so that the model geometry can be adapted to the desired anthropometric parameters. In addition to the geometry, other model parameters such as: Mass and Inertia properties, Joint characteristics (stiffness, friction, damping and hysteresis) and Contact characteristics are scaled.

Design optimisation

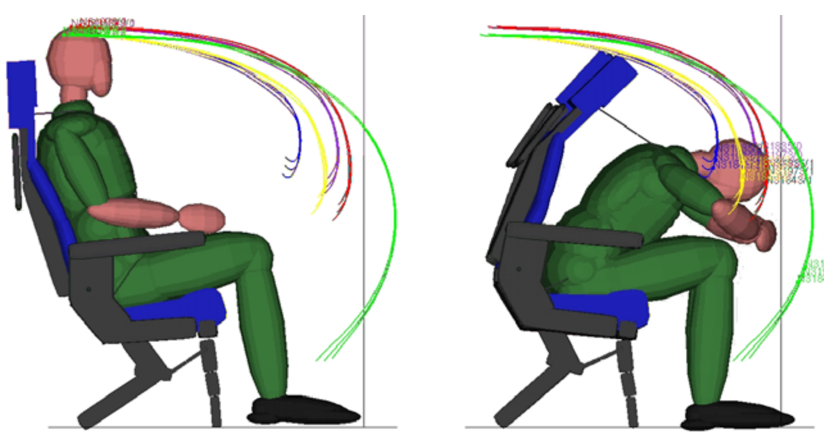
To support the design iteration process of GOING-SAFE, TNO Automotive Safety assessed a number of design-issues with parameter study simulations using the validated DYNASAFE seat model. The design issues covered are:

- Shoulder belt inertia reel performance
- Head impact on row in front
- Lumbar spine compressive load in vertical crash condition
- Tibia impact on lower side of front row seat pan

Each of the design issues is discussed shortly below.

Shoulder belt inertia reel performance

The inertia reel in the backrest stores the shoulder belt when it is not used. When the shoulder belt is used to restrain the occupant the inertia reel can provide the comfort of free movement of the occupant upper torso in normal operational conditions. In crash conditions however the inertia reel must block the shoulder belt to offer the occupant a safe response to the crash deceleration. The time to block the inertia reel and the elongation of the belt that remains on the inertia reel drum results in a spool-out of the belt before it becomes effectively blocked. This results in extra forward motion of the occupant's upper torso. The question to be answered was whether the spool-out of the inertia reel is acceptable.



Green 50%ile Lap belt only

Yellow 50%ile 3-PSH DiscoLock soft Inertia reel blocked
Blue 50%ile 3-PSH DiscoLock strong Inertia reel blocked
Red 95%ile 3-PSH DiscoLock strong Inertia reel spool-out
Pink 95%ile 3-PSH DiscoLock strong Inertia reel blocked

Figure 4: Simulation with 95%ile occupant in front row configuration (Bulkhead on 920 mm from rear leg tie-down point)

In Figure 4 the simulation with the large male (95%ile) occupant is shown in a configuration allowing a shoulder belt spool-out of 50 mm before blocking. This is a well know value for inertia reel application in the automotive field. The head-bulkhead clearance predicted by the simulation is 65 mm. The 50%ile occupant lap belt only simulation ran for reference showed a head-bulkhead interference of 77 mm resulting in a HIC value of 2250. This HIC value is far beyond the injury limit of 1000. It is concluded that a standard automotive inertia reel spool-out of 50mm is acceptable.

Head impact on row in front

In the standard cabin layout the seat rows are positioned at pitches from 30" to 34". The seat in front is close enough to the occupant to strike it in horizontal pulse crash conditions. The safety regulations require measure to reduce the severity of the head impact on the row in front. Under the current regulation the braced position of the occupant is one of the measures to comply with the regulations. The pulse severity of 9G is well known in the current safety standard. The GOING-SAFE seat design incorporating a three point restraint system is designed to comply with the increased 16 G dynamic seat test requirements throughout the whole cabin. Simulations were carried out to investigate the performance of the design with regards to head impact on the row in front and the optimisation of the foam padding at the aft face of the backrest was considered.

The simulations were done with the following mixed occupation: in the rear row left hand seat 50%ile, middle seat 95%ile and right hand 5%ile. The front row was not occupied. The energy-absorbing device in the backrest hinge results in a very limited forward motion of the backrest of the not occupied seat.

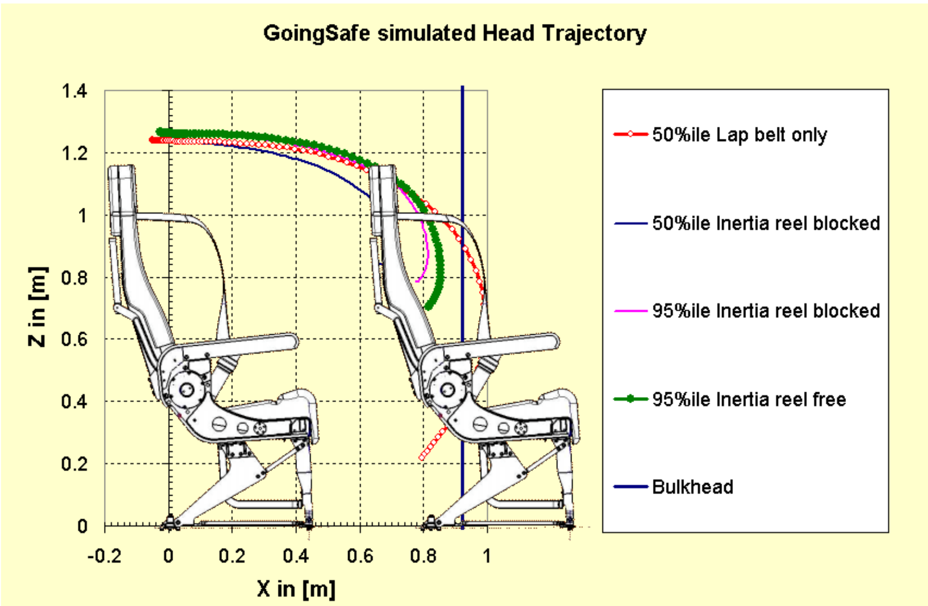


Figure 5: Head trajectories projected on a row to row configuration (32” pitch)

In Figure 5 the top of head trajectories of 50%ile and 95%ile occupants are shown in configurations with pre-blocked and free inertia reel (50mm spool-out). The 50%ile occupant lap belt only simulation is shown for reference. All the simulated configurations show a contact of the head with the rear side of the seat back. The 50%ile lap belt only configuration results in quite severe contact with a head impact criterion (HIC) value of 1714. This HIC value is far beyond the injury criterion limit of 1000. In the 3-PSH cases the contact is rather less severe. With the application of appropriate foam padding at the rear side of the backrest the HIC can be reduce to fairly low values. In Table 1 the HIC values obtained from simulations for three occupant sizes and three seat row pitches are shown for standard inertia reel settings (50mm spool-out). In Table 1 two foam options are shown: 50mm soft foam and 25mm hard foam. It is concluded that 25mm hard polyurethane foam is adequate to reduce the head contacts to an acceptable level.

Table 1: Head impact results in row to row configuration - HIC values (grey shading: no contact)

Standard inertia reel setting (50 mm spool out)	50mm soft polyurethane			25mm hard polyurethane		
	34”	32”	30”	34”	32”	30”
Large male (95%ile)	1544	1505	1206	737	775	716
Average male (50%ile)	180	380	867	168	415	564
Small female (5%ile)	239	260	286	265	305	297

Lumbar spine compressive load

On the reinforced DYNASAFE seat, the vertical pulse crash condition may well result in high lumbar spine loads because of the reduced seat flexibility. In the DYNASAFE tests at CEAT in Toulouse a lumbar spine compressive load of 6030 N was measured. The injury criterion limit is 6700 N. With simulations it is investigated whether the lumbar spine compressive loads can be reduced by optimisation of the seat pan foam properties.

A concept with dual stiffness foam consisting of a soft polyurethane foam layer for comfort and a hard polyurethane foam layer was simulated (see Figure 6). The simulation with the dual stiffness foam configuration predicts a lumbar spine load reduction of 17% with respect to the tested single stiffness seat pan foam.

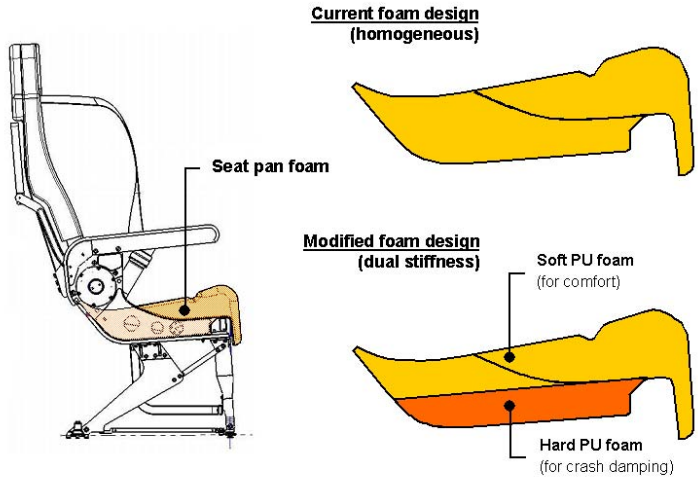


Figure 6: Dual-stiffness-foam concept combination of comfort and crash damping

Tibia impact on row in front

The only leg related measurement in regulatory dynamic seat testing is the femur compression. The femur compression is high in cases that the knee contacts the seat in front. Contacts of the lower legs with the seat in front do normally not result in significant femur compression. In those cases the lower legs swing onto the aft lower side of the seat in front. The GOING-SAFE seat design anticipates softening this contact to prevent or reduce lower leg injuries. Simulations are performed to investigate the lower leg loads and to optimise the padding at the aft lower side of the seat pan.

In the DYNASAFE tests at CEAT the femur loads measured in both legs show up the moment of contact, through a sudden decrease of the tension loads. The femur the maximum compression measured is 1.35 kN. This femur compression is small compared to the FAR/JAR 25.562 criterion limit of 10 kN. At the moment of contact between the tibia and the seat in front, the tibia experiences extensive bending. The high reaction loads on the knees result in stretching out of the legs. The feet swing up onto the lower side of the seat in front. During the rebound the feet rotated back onto the end of the range of motion. This can result in high ankle lock-up bending moments. Because the tibia-seat pan contact occurs somewhere in the middle of the tibia the bending moment at the contact location will be the critical bending moment.

To investigate the lower leg to seat pan contact and to optimise the foam to be applied at this location, simulations were performed with the mixed occupation: in the rear row left hand seat 50%ile, middle seat 95%ile and right hand 5%ile. None of the seats of the row in front were occupied (see Figure 7).

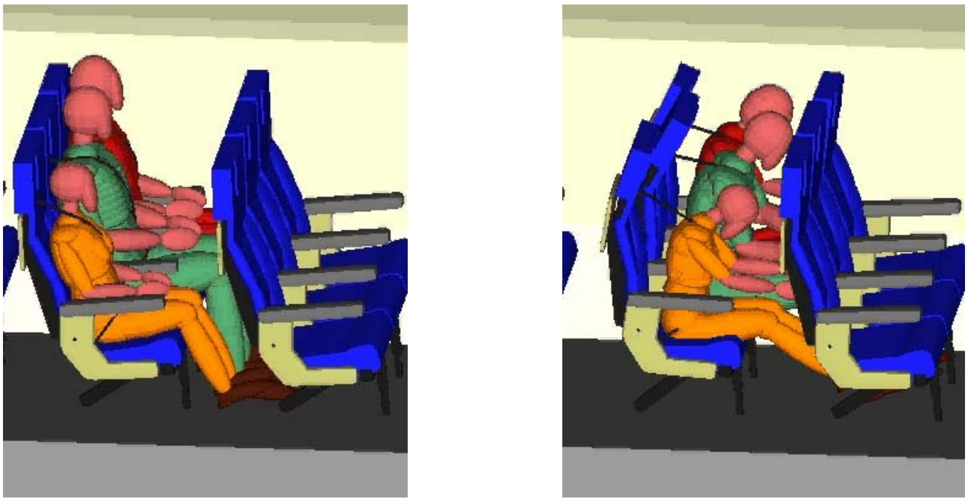


Figure 7: Row to row simulation: 5%ile aisle (near), 95%ile mid, 50%ile window (far)
Left: initial position; Right: moment in time of lower leg contact

In Table 2 the results of the simulations with soft foam with a thickness of 10 mm (standard) and hard foam 10 and 20 mm thick are presented. From the quite simple simulation model there is no loading output available along the tibia. The output parameters available obtained from the model are loads at the upper and lower side of the tibia and the tibia to seat pan contact load. The critical loading the bending moment somewhere mid way the lower leg can not be directly analysed. Therefor qualitative figures on improvements are given based tibia shear forces and bending moments at the upper and lower side and the contact loads.

The results show that critical loads for the 50%ile dummy are found in the lower tibia and for the 95%ile dummy in the upper tibia. The results for a 5%ile dummy are very low and considered to be not relevant. The simulations indicate that the lower leg loads are most likely close to or over the injury criterion limits (95%ile: 307 Nm; 50%ile: 225 Nm) even when foam padding is applied.

From this study it is concluded that the femur compressive loads measured in dynamic seat tests are not adequate to assess leg injuries. Tibia impact on the aft lower side of the seat in front can cause disabling injuries. Disabling injuries may prevent the occupant to escape a post crash fire. Soft foam padding with a thickness of 10 mm does not have any positive effect on the leg loads. A thickness of 20mm hard foam padding reduces the lower leg loads by about 20%.

Table 2: Relative simulation results: lower leg contact loads, tibia shear and bending

Foam configuration	Average male (50%ile) dummy			Large male (95%ile) dummy		
	Contact load	Lower tibia		Contact load	Upper tibia	
		Fx	My		Fx	My
Soft foam 10 mm (Standard)	100%	100%	100%	100%	100%	100%
Hard foam 10 mm	87%	88%	90%	100%	99%	99%
Hard foam 20 mm	71%	72%	80%	78%	78%	83%

GOING-SAFE design evaluation

Design evaluation simulation matrix

After the adaptation of the design configuration in accordance with the design optimisation simulation results the GOING-SAFE seat design was frozen. This final design is evaluated on the compliance with the airworthiness requirements according FAR/JAR 25.561/562 [1] and on broader aspects with regards to cabin safety and floor loads. The evaluation is performed for the all seat configurations throughout the cabin: standard-, narrow-, extra narrow- and emergency exit row configuration in row to row and bulkhead layout. The bulkhead layout is analysed without and with 10 degrees floor deformation. Further more the design is evaluated for a range of occupant sizes: 95%ile, 50%ile and 5%ile and critical seat row occupations. In total 76 MADYMO simulations are performed. The matrix assessed to explore the design performance is given in Table 3 (see Appendix).

Simulation results

The results obtained with the 76 simulation runs are reviewed on maximum and minimum values of 92 parameters and examined on occupant kinematics and contact locations. The cases with average male (50%ile) dummy are important for regulatory compliance evaluation. The large male (95%ile) and small female (5%ile) cases are used to assess the full operational envelope. Differences in results depend on seat location window, middle or aisle. These differences must be contributed to seat row deformation. First of all there is the seat row bending in the vertical plane that is responsible for the differences in the vertical cases. The seat torsion induced by the shoulder belt load that is applied at the aisle side of each seat. The energy-absorbing hinge is also located at the aisle side of the seats. The backrest hinge moments of the window and middle seat are directly introduced in the seat-spreaders and led through to the seat legs. The aisle seat backrest moment, however, has a longer load path: from the aisle side hinge to the side structure through the seat pan shell to the leg spreader. The longer load path is more flexible, therefor the forward displacements larger and the related parameters of load and accelerations different of the aisle seat and its occupant.

Vertical crash cases

The lumbar spine compressive loads found in the simulations are between 3067 N (one 95%ile in the double seat row) and 5560 N (Mid of three 95%ile's in standard seat). Looking at the 50%ile cases only the maximum lumbar load is 5362 N (Mid seat standard row). The application of the dual stiffness seat pan foam is effective: the 50%ile result matches with the design iteration result as described above being 11% lower than the DYNASAFE test result. The 50%ile values are well below the injury limit of 6672 N. In full occupied standard rows the lumbar load in the middle seat is higher than that in the left hand and right hand seat (80% for 95%ile; 10% for 50%ile and 0% for 5%ile). This is caused by the seat flexibility. In the narrow and extra narrow seat rows this effect is less pronounced. As expected the lap belt only cases don't show significant differences. The three-point shoulder harness is not more effective than the lap belt only in this crash condition.

It is concluded that the GONING-SAFE concept will pass the vertical certification test to show compliance with the vertical FAR/JAR requirements.

Horizontal crash cases

The issues dealt with in this section are: Shoulder belt loads, Floor loads, Head-bulkhead clearance and Head injury criterion (HIC) values in row to row. Where applicable the horizontal cases will be completed with a comparison with lap belt only results.

Shoulder belt loads

The energy absorbing backrest hinge operates with a more or less constant torque. In this way the backrest hinge energy absorber limits the shoulder belt loads. Therefor the maximum shoulder belt loads in the horizontal crash conditions are almost the same in all cases:

- Large male (95%ile) 3148 to 3357 N
- Average male (50%ile) 3240 to 3564 N
- Small female (5%ile) 3632 to 3843 N

The smallest shoulder belt load 3103 N is found in a special horizontal crash condition with floor deformation. As this is a special case the comparison above consists of cases without floor deformation. The simulations show the largest shoulder belt loads for the small female (5%ile) occupants. The difference in shoulder belt load between the body-sizes can be explained with initial shoulder belt routing over the body. The large male (95%ile) occupant has the largest shoulder height. The shoulder belt will run from the inertia reel in the backrest almost perpendicular to the backrest towards the occupant's shoulder. For the small female occupant, however, the shoulder belt will run under a significant angle towards the considerable lower occupant's shoulder. To exceed this torque value the oblique belt load with the 5%ile must be larger than a perpendicular belt load with the 95%ile.

Comparison of the belt loads with the FAR/JAR injury criterion of 7784 N shows an ample safety margin.

Floor loads

The loads that are applied to the aircraft floor structure are important for the GOING-SAFE concept because too high floor loads would prevent application of the concept in exiting aircraft. In

Table 4 the maximum floor loads and the critical configuration are given. For the comparison with the regulatory requirements only the 50%ile occupant cases are important. The maximum load applied to the floor is 36618 N (Extra narrow seat on 34" pitch with 3 50%ile occupants). The allowable for dynamic conditions is the bracket-floor beam tear-out strength of 17.5 kN per stud [4]. The three-stud seat to floor attachment bracket of the GOING-SAFE seat design shows adequate strength to comply with the regulation.

Head-bulkhead clearance

The clearance of the occupant's head with the bulkhead put on a distance of 940 mm from the rear tie-down point is given in Table 5. The minimum clearance found is 116 mm for a certification load case with floor deformation applied.

If the occupants are restrained with a lap belt only the head impacts the bulkhead. The head injury values are for the large male (95%ile) occupant close to or over the injury criterion limit of HIC 1000. The interference of the head trajectory with the bulkhead is approximately 55 mm for the 50%ile and 140 mm for the 95%ile. If the seat row is closer to the bulkhead the HIC values will be significantly higher as shown in the design optimisation simulations where an interference of 77 mm resulted in a HIC value of 2250 for the 50% occupant.

Head injury criterion (HIC) values in row to row

The contact of the occupant's head with the rear side of the backrest of the seat in front can occur at different locations: at the foam padding above the meal-table, at the meal-table or its edges and backrest base below the meal-table in case the backrest is folded forward completely. The later contact occurs in conventional interior configurations when the deceleration is enough to bring the backrest in complete fold forward position. In

Table 6 the HIC values predicted by the simulations are summarised for all the three-point shoulder harness cases, the average male (50%ile) occupant and the lap belt only cases. All three-point shoulder harness cases are simulated with a not occupied row in front. This is critical case because if the seat in front is occupied the seatback moves forward. As a result of this the contact will be less sever. For reference the lap belt only cases are summarised.

All GOING-SAFE three-point shoulder harness seat configurations show HIC values as low as 312 maximum for all occupant sizes. The three-point shoulder harness, the backrest hinge energy absorber and hard foam padding above the meal-table provides ample head impact protection to pass a certification test with a 16G-deceleration pulse.

The lap belt only cases show HIC values far beyond the criterion of 1000. If the seat in front is not occupied (see left hand seat simulation) the occupant contacts the seat in front on the foam and later the table. The predicted critical HIC is 1400 for an average male 50%ile occupant with a 30-inch seat pitch. If a 50% ile occupant takes the seat in front (see right hand seat simulation), the head contacts fully on the table. The critical HIC value predicted becomes 2213. If the backrest, of a non-occupied seat, rotates forward due to the pulse deceleration (see middle seat simulation) the head contacts the backrest base under the table. At this seat structure location there is no padding to soften contact of the high-speed almost perpendicular impact. The resulting predicted HIC value is 6755.

Discussion

The design of aircraft interiors is a process to be performed within tight constraints with regards to comfort, styling, safety, evacuation, handling procedures, maintenance, seat row mass, production cost, time to market and regulatory requirements. The issue of occupant crash safety is more often than not reduced to the compliance with limited set of FAR/JAR requirements.

For exiting seat designs the compliance with the regulatory occupant crash safety requirements is often obtained through a trial and error procedure during the dynamic seat testing in the laboratory. To obtain for example HIC value below the injury criterion limit of 1000 the backrest hinge friction is changed to tune the impact resistance of the seatback in front of the occupant. This exercise can involve quite a number of tests and can be relative costly. The limited view on safety issues can result in lack of attention to safety aspects in the detailed design of parts that are not in play for the regulatory safety performance. For example the severity of the tibia impact on the aft side of the seat pan in front of the occupant is time and again ignored. Even sharp edges are sometimes present in the design of a foldable footrest.

The protection offered by the seat with regards to leg injuries is not at all assessable through the femur compression requirement in the dynamic seat test requirements. The risk of even light leg injuries in aircraft crashes however can be disable occupant to escape the crash site that may cause fatality through a post crash fire or drowning. An integral approach of occupant crash safety in aircraft seat design, similar to that commonly applied in automotive design can increase the occupant protection in emergency landing and crash conditions considerably.

In the GOING-SAFE seat design process it is demonstrated that the implementation of the innovative 3-point shoulder harness system in an aircraft seat design can be combined with an effective integral safety concept approach. The tight time constraints of the design process can be complied with by application of a predictive simulation tool to analyse the dynamic performance of the design. Application of such tools in the automotive sector has demonstrated the suitability of simulations for design optimization and the adequate prediction accuracy for compliance test. To obtain a predictive model it is imperative to validate the model against component and or full-scale test results. The GOING-SAFE design process demonstrates the decisive quality of the simulations with a relative simple MADYMO model.

The GOING-SAFE design team faced with the challenge to cope with the mass target of about 45 kg per triple seat succeeded to define a configuration with a competitive seat row mass. The application of advanced materials and production techniques was necessary to reach this target. Due to these advanced technologies of these innovations is the cost price of the seat almost double the price of a conventional designed seat. Besides the large step forward in occupant crash protection the 3-PSH-system offer benefits in cabin crew procedures. The check on the application of the seat belts is much easier because the easily visible shoulder belt can not be applied without the lap belt properly installed.

The application of the GOING-SAFE design in flying aircraft may encounter resistance from airline operators, travelers and authorities. All parties will have their own view on the concept. Is the additional cost worth for the safety improvement? Air traveling is already one of the safest means of transport. Do travelers change their perception when 3-PSH systems are introduced or would they see the logic of wearing shoulder belts in air transport conditions as in their private cars? Would authorities weight the occupant protection to prevail over the economic impact? It would be very helpful to find an airline operator that is willing to set-up demonstrator application of the GOING-SAFE design to get practical experience with the innovative occupant protection system in the day to day use of it and the travelers perception that it prompts.

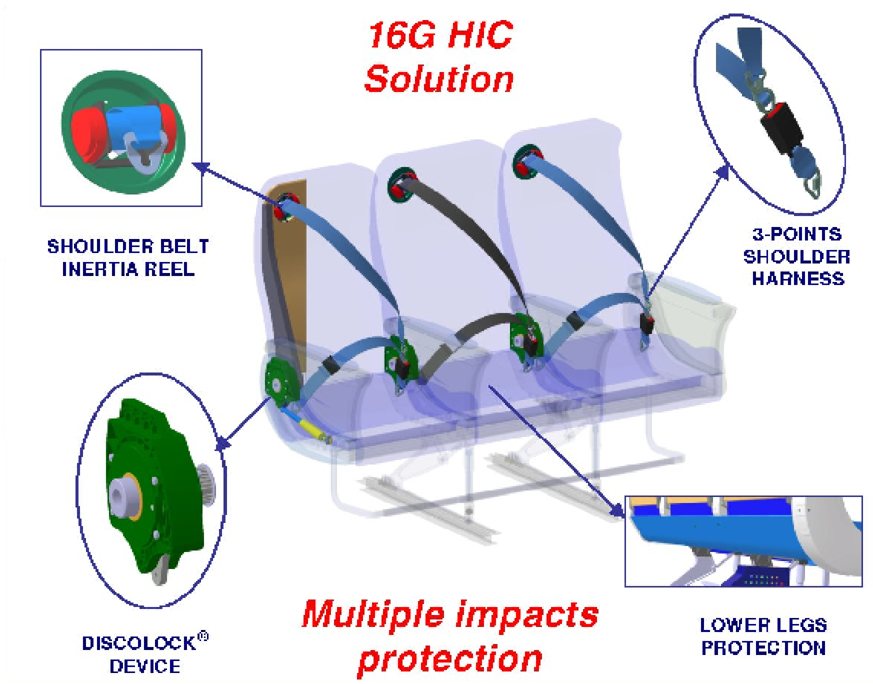


Figure 8: GOING-SAFE triple seat design for A320 family

Conclusions

From the design optimisation and concept evaluation research presented in this paper the main conclusions are:

- Standard automotive techniques are adequate to support the aircraft seat design process to achieve compliance with occupant crash safety design targets.
- The femur compressive loads, according to FAR/JAR requirement, measured in dynamic seat tests are not adequate to assess leg injuries. Tibia impact on the aft lower side of the seat in front can cause disabling injuries that may prevent the occupant to escape a post crash fire or drowning.
- The GOING-SAFE three-point shoulder harness system prevents head to bulkhead contact for all occupants.
- The GOING-SAFE three-point shoulder harness system in a row to row configuration shows head injury criterion values smaller than 315 for all occupant sizes.
- The GOING-SAFE seat will pass the vertical certification test. The 50%ile maximum lumbar spine compression load in vertical crash condition being 5362 N show enough margin with respect to the injury criterion limit 6672 N. (95%ile: 5560N)
- The GOING-SAFE three-point harness system maximum shoulder belt load for 50%ile 3564 N show ample margin with respect to the injury criterion limit 7784 N (5%ile: 3843 N)
- The GOING-SAFE seat floor loads, applied to a three-stud set to floor attachment bracket, are low enough to comply with the regulatory requirements.

Acknowledgements

The European Community through the Competitive and Sustainable Growth Project number GMA2-CT-2000-32042, GOING-SAFE sponsored this study. The following partners contributed to the GOING-SAFE program:

- Structural Design & Analysis (SD&A) (Brussels, Belgium)
  – Project co-ordinator, Design and Engineering;
- AvioInteriors (Latina, Italy) – Aircraft Seat Manufacturing;
- F. Braun (Brussels, Belgium) – Consultant;
- TNO Automotive Safety (Delft, The Netherlands)
  – Design optimisation and crash simulation.

Appendix

Table 3: Matrix of 76 simulations
V = vertical: 60°down 14G/160ms, H = horizontal: 16G/180ms,
FD = floor deformation 10 degrees (right hand front leg in tension),
BH = bulkhead on 940mm from rear tie-down point

Seat configuration		Occupant size and position (window / middle / aisle): 50/50/50 Certification	95/95/95	5/ 5/ 5	- /95/95	- / - /95
Number off		21	6	6	13	15
Standard with bulkhead	11	V+H H(FD)	V+H	V+H	V+H	V+H
Standard row to row	15	H 34-32-30	H 34-32-30	H 34-32-30	H 34-32-30	H 34-32-30
Emergency exit row (reduce pre-recline)	4	V H 35	H 35	H 35		
Narrow row	13	V H 34-32-30 H(BH FD)			V H 34-32-30	V H 34-32-30
Extra narrow row	13	V H 34-32-30 H(BH FD)			V H 34-32-30	V H 34-32-30
Dual seat row (34" pitch)	5	50/50: V+H +H(BH FD)				95/ - : V+H
		5	5	5		
Lap belted only	15	V+H(BH) H 34-32-30	V+H(BH) H 34-32-30	V+H(BH) H 34-32-30		

Table 4: Maximum floor loads and load case indication (all horizontal, 10 degr yaw)
Std = Standard; EN = Extra Narrow; BH = Bulkhead FD = Deformed Floor

Maximum floor loads In Newtons	Left hand legs: Front	Left hand legs: Rear X	Left hand legs: Rear Z	Right hand legs: Front	Right hand legs: Rear X	Right hand legs: Rear Z
50%ile only						
3-Point shoulder harness	-35743	29029	29404	-32272	33409	**36618**
Load case	Std 34" 3x50	Dual 34" FD 2x50	Dual BH FD 2x50	EN 34" 3x50	EN 34" 3x50	EN 34" 3x50
Lap belt only	-24802	17165	19815	-21781	22249	25643
Load case	Std 34" 3x50	Std 34" 3x50	Std 34" 3x50	Std 30" 3x50	Std 30" 3x50	Std 30" 3x50
All body sizes						
3-Point shoulder harness	-43261	30142	34012	-40495	44461	44159
Load case	Std 34 3x95	Std BH 3x95	Std BH 3x95	EN 34 2x95	EN 34 2x95	EN 34 2x95
Lap belt only	-32987	23166	26641	-28028	29999	32849
Load case	Std 34 3x95	Std BH 3x95	Std BH 3x95	Std 34 3x95	Std 34 3x95	Std 34 3x95

Table 5: Head – Bulkhead clearances and HIC values
(Bulkhead position 940 mm from rear tie-down point)

Configuration	LH seat	Middle seat	RH Seat

	(window)		(aisle)
Without Floor Deformation in [mm]			
Standard 3x95%ile	167	177	157
Standard 3x50%ile	**261**	**261**	**236**
Standard 3x 5%ile	433	433	433
With Floor Deformation in [mm] (50%ile occupant only)			
Standard 3x50%ile	**132**	**139**	**118**
Narrow 3x50%ile	132	137	117
Extra narrow 3x50%ile	128	129	116
Dual 2x50%ile	139	152	(No seat)
Lap belt only HIC values in [s] (upright seating position)			
Standard 3x95%ile	1007	929	1030
Standard 3x50%ile	**430**	**418**	**460**
Standard 3x 5%ile	392	397	370

Table 6: Head injury HIC values and contact indication in row to row configurations Std = Standard; (E)N = (Extra) Narrow; EE = Emergency exit row

Configuration	**LH seat (window)**	**Middle seat**	**RH Seat (aisle)**
All 3-Point Shoulder Harness cases			
Pitch 34"	**288** (EE 35 3x95) Foam and later table	**312** (EE 35 3x95) Foam and later table	281 (EE 35 3x95) Foam and later table
Pitch 32"	264 (Std 3x95) Foam	240 (EN 2x95) Foam and later table	269 (EN 2x95) Foam and later table
Pitch 30"	248 (Std 3x95) Foam	241 (N 2x95) Foam	**311** (N 3x50) Foam
50%ile occupants (full occupied seat row)			
Pitch 34"	79 (EN) No significant contact	84 (EE 35) No significant contact	135 (N) Foam and table edge (minor)
Pitch 32"	135 (Std) Foam and later table	145 (Std) Foam and later table	193 (N) Foam and later table
Pitch 30"	216 (EN) Foam	237 (N) Foam	**311** (N) Foam
Lap belt only (95/95/95%ile, 50/50/50%ile or 5/ 5/ 5%ile all in upright seating position)			
Configuration of row in front (See note)	Seat in front <u>not</u> occupied	Conventional seat in front <u>not</u> occupied	Seat in front occupied (50%ile)
Pitch 34"	1074 (3x 5) Table	4508 (3x95) Backrest base	**2213** (3x50) Table
Pitch 32"	1063 (3x95) Foam and later table	**6755** (3x50) Backrest base	1435 (3x50) Table
Pitch 30"	**1400** (3x50) Foam and later table	5651 (3x50) Backrest base	1654 (3x 5) Table

Note: In all the 12 explored lap belt only cases the row in front has different configurations per seat:
Left hand seat : GOING-SAFE seat with energy-absorbing hinge. <u>Not</u> occupied seat.
Middle seat : Seat with no energy-absorbing hinge, not occupied. To simulate conventional seat configuration: Seat back rotating forward driven by deceleration pulse.
Right hand seat : GOING-SAFE seat with energy-absorbing hinge. Seat occupied with 50%ile occupant.

References

1 Title 14 U.S. code of Federal Regulations, Part 25, Amendment 25-64, Section 25.562, published in the Federal Register of May 17, 1988, effective date of June 16, 1988.

2 E. van Hassel, Application of MADYMO in the Design of a Crashworthy Aircraft Passenger Seat, ECCOMAS 2000, Barcelona, September 2000

3 MADYMO Version 6.0, TNO Automotive, Delft, The Netherlands, 2001

4 Airbus A320 Frame Specification document AI 2520 M1F 000100 Issue 8 page 46 paragraph 6.2.5: Allowable loads for aircraft seat tracks at one double stud attachment. It must be justified that the following values will not be exceeded (in static 9G crash conditions): X = 20 kN, Y = 3.5 kN, Z = 25 kN. (Single stud tear-out strength 17.5 kN, double stud 35 kN)