Studies about the Utilisation of the Aircraft Cargo Compartment as Additional Passenger Cabin by Use of Numerical Crash Simulation

Marius Lützenburger

German Aerospace Center (**DLR**)
Institute of Structures and Design
Pfaffenwaldring 38-40
70569 Stuttgart
Germany

Abstract

The worldwide growth in air transportation as well as the need of further reductions in the specific fuel consumption requires a more efficient use of aircraft. One of the ideas – the increase of the passenger capacity – is to use portions of the cargo compartment of wide-body aircraft as additional passenger cabin. Airbus and Boeing have both patented lower deck seating concepts in recent years.

The DLR Institute of Structures and Design participated in the project 'Innovative Cabin Technologies' within the German aeronautical research programme 'LuFo III'. In the project, DLR investigated options to equip the cargo compartment in the front part of the fuselage with passenger seats by means of different numerical crash simulation methods (hybrid and FE). This paper concentrates on the crash simulation studies which were carried out with the hybrid simulation program DRI-KRASH [2]. These studies were used to select the most promising fuselage design concept.

The primary aspect of 'Lower Deck Seating' (LDS) is the safety of the passengers, which – in case of a crash landing – should be comparable to the passenger safety in conventional aircraft. DLR developed an innovative concept for the assessment of occupant safety. The safety potential of each seat is judged on the basis of a point scheme, which assesses the following 4 criteria: Accelerations, preservation of a living space, injury risk from falling objects (e.g. overhead bins or hand luggage) and preservation of an escape route. The evaluation scheme therefore includes the entire occupant environment and also covers important aspects of crash certification.

Different crash models of the fuselage section, the seats and the occupants were set up in a parametric way. Crash simulation calculations with numerous configurations were carried out in an extensive parametric study and in each case evaluated according to the described assessment scheme. Thus, it was possible to develop important design rules, which in case of their implementation should contribute to a possible use of the cargo compartment as passenger cabin in the future.

The work presented here is part of the project "Innovative Cabin Technologies" (KATO) which was funded by the German Federal Ministry of Economics and Technology – Reference No. 20K0302V

Contents

List of Figures

1 Introduction

On many flight routes the aircraft cargo compartment is not used to full capacity. Therefore, sections of the cargo compartment could be used as additional passenger cabin space. In wide-body aircraft, where the height of the cargo compartment is sufficient for people to stand, the passenger capacity could such be increased. The aircraft could be used more efficiently and the specific fuel consumption reduced.

The primary aspect of ‘Lower Deck Seating’ (LDS) is the safety of the passengers. In case of a crash landing, the main concerns are the acceleration level and the survival space which – at first view – both seem unfavourable compared to the conditions on the passenger main deck. It is evident that additional measures are required in order to secure the survival space in the lower deck area. The fuselage design must also provide for zones where the impact energy can be absorbed.

Figure 1 shows two lower deck seating concepts which were patented by Airbus and Boeing.

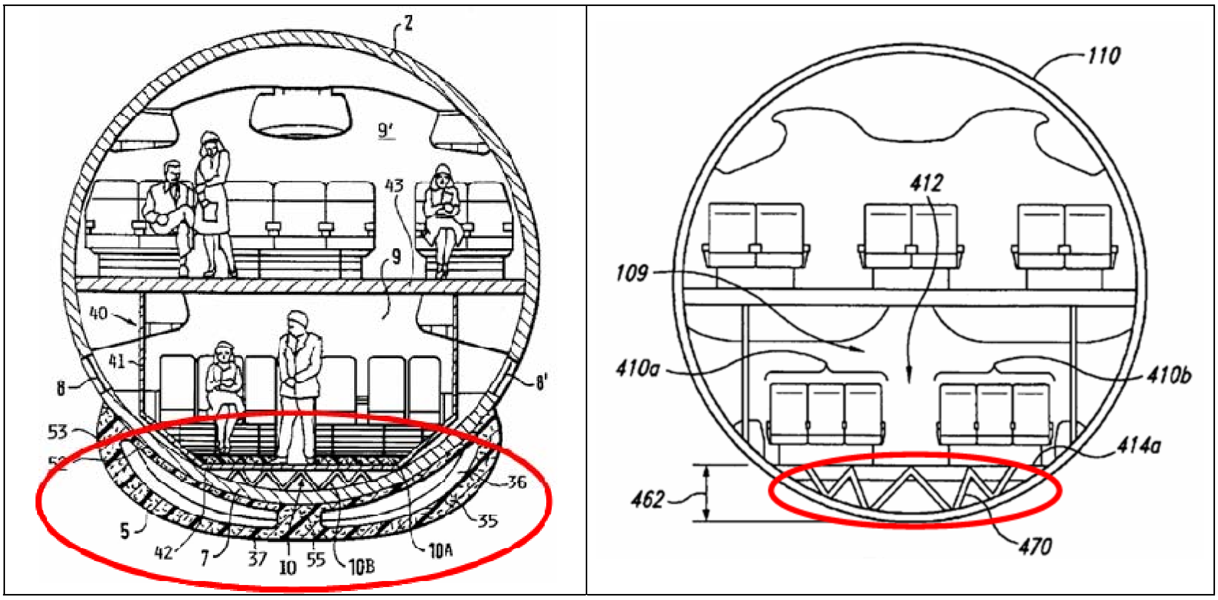


Fig. 1: Lower Deck Seating Concepts – Patents from Airbus and Boeing [3], [4].

In the Airbus patent, an energy absorbing structural unit is attached to the fuselage underside. This concept has the advantage that the accelerations can be reduced to acceptable levels. Disadvantages are the additional weight and the increased aerodynamic drag which lead to a higher fuel consumption.

In the conception which was patented by Boeing, the energy absorbing structure (‘470’) is located below the lower floor, within the original fuselage contour. Thus, there is only little additional weight and no additional drag is generated. It has to be analysed whether this concept can meet the safety requirements.

A large number of different lower deck seating / fuselage design concepts was analysed with the hybrid crash simulation program DRI-KRASH [2] and finally the most promising configuration chosen. The set-up of the KRASH models is described in the following.

Remark: After an estimation of the extra weight, the ‘Airbus concept’ was not considered in the here presented work.

2 Set-up of the DRI-KRASH Models

The LDS simulations were carried out with KRASH models of a wide-body fuselage section which includes the seats and occupants. A KRASH model is mainly made up of masses, nodes and their connecting beams and spring elements.

In order to be as flexible as possible, the models were set up in a parametric way: Separate models of the fuselage section and the seats and occupants were created. For the fuselage section model, the number of frames and their distance can be chosen, as well as the seat rail positions and other parameters.

Then, a model of a double and a triple seat was created which each includes a simple occupant and belt representation. These separate models were then selectively put together to form different configurations.

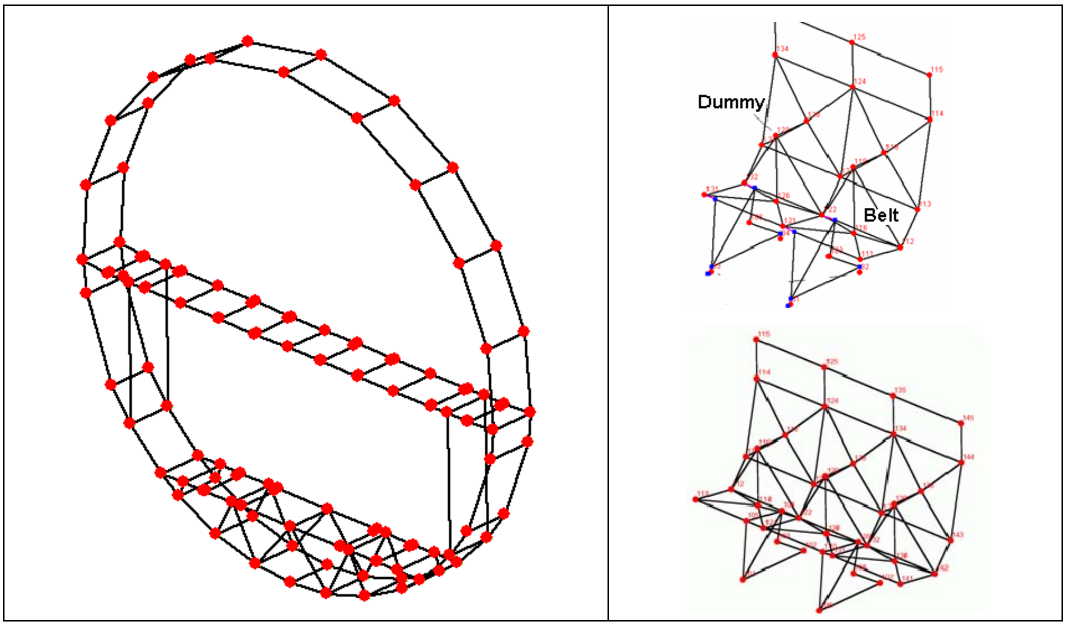


Fig. 2: KRASH fuselage section and seat models.

The following figure shows the basic configuration with 8 seats on the main deck and 4 seats on the lower deck. Another option could be the use of two triple seats on the lower deck.

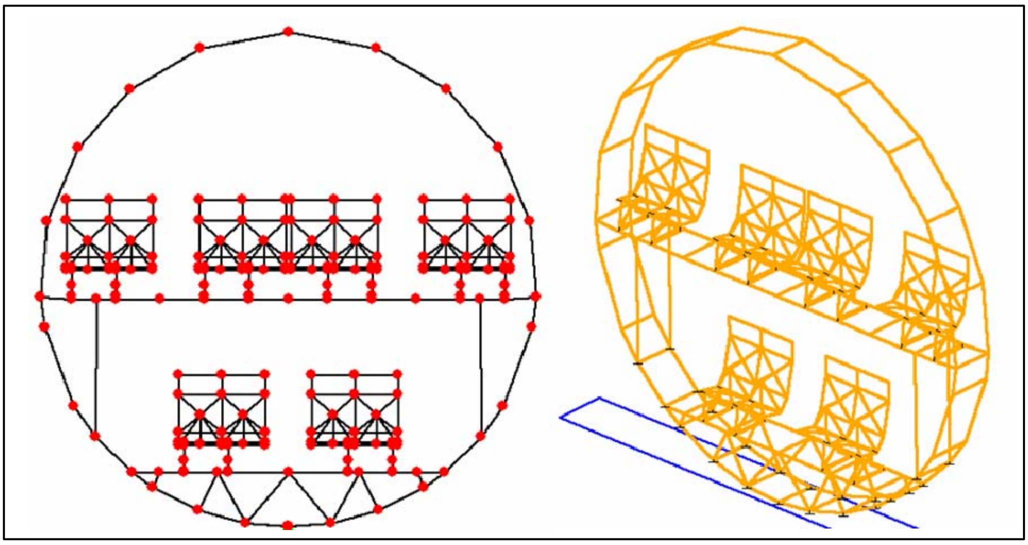


Fig. 3: KRASH model – basic LDS configuration.

3 Lower Deck Seating (LDS) – Parametric Study

In the parametric study, nearly 200 different configurations were simulated. Some of the varied parameters are illustrated in the following figure:

- The properties of the lower deck **floor cross beams.**
- The placement of the **lower deck floor struts** and their energy absorbing capability (force-deflection characteristics).
- The **aisle width** on the lower deck (constant on the main deck).
- Additional **struts** between lower and main deck => number, positions, force-deflection characteristics.

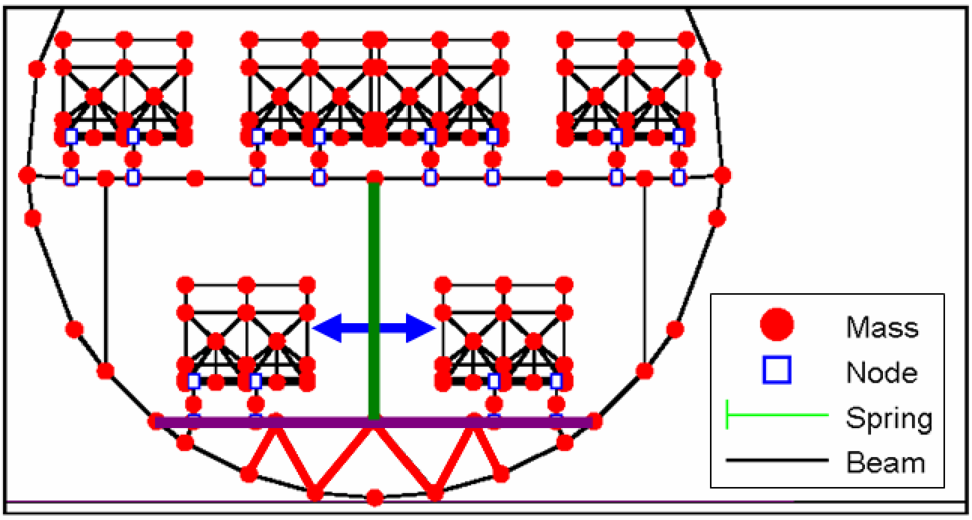


Fig. 4: Varied parameters in LDS study.

A vertical impact speed of **6.7 m/s** (22 ft/s) was used in all shown simulations.
On the following pages, the results of two configurations are compared, in which the properties of the lower deck floor cross beams are varied. In configuration LDS_028, these beams are allowed to rupture whereas in LDS_030 the cross beams are reinforced in such a way that they cannot fail at the occurring crash loads.

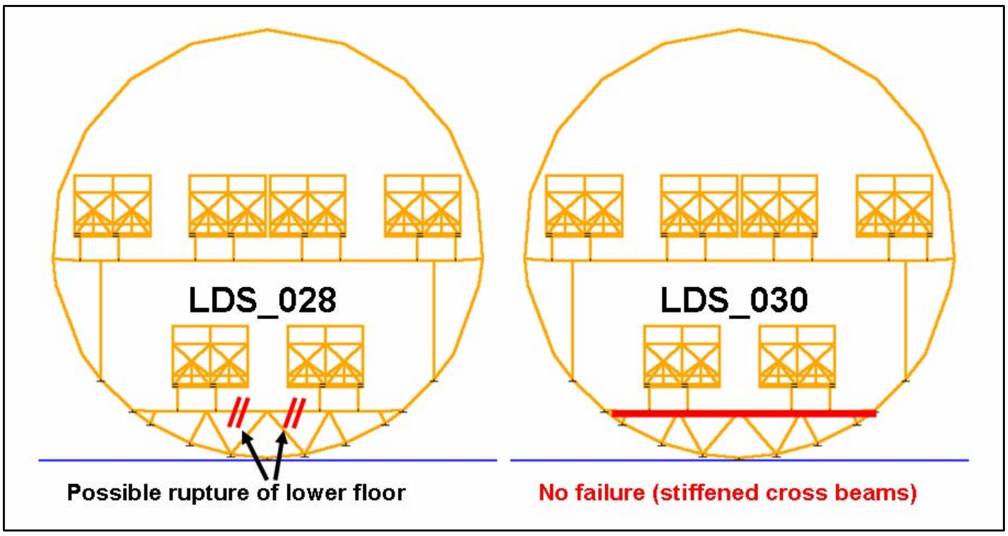


Fig. 5: 2 LDS configurations with different properties of LD floor cross beams.

'With rupture of lower floor cross beams' **'No failure of lower floor cross beams'**

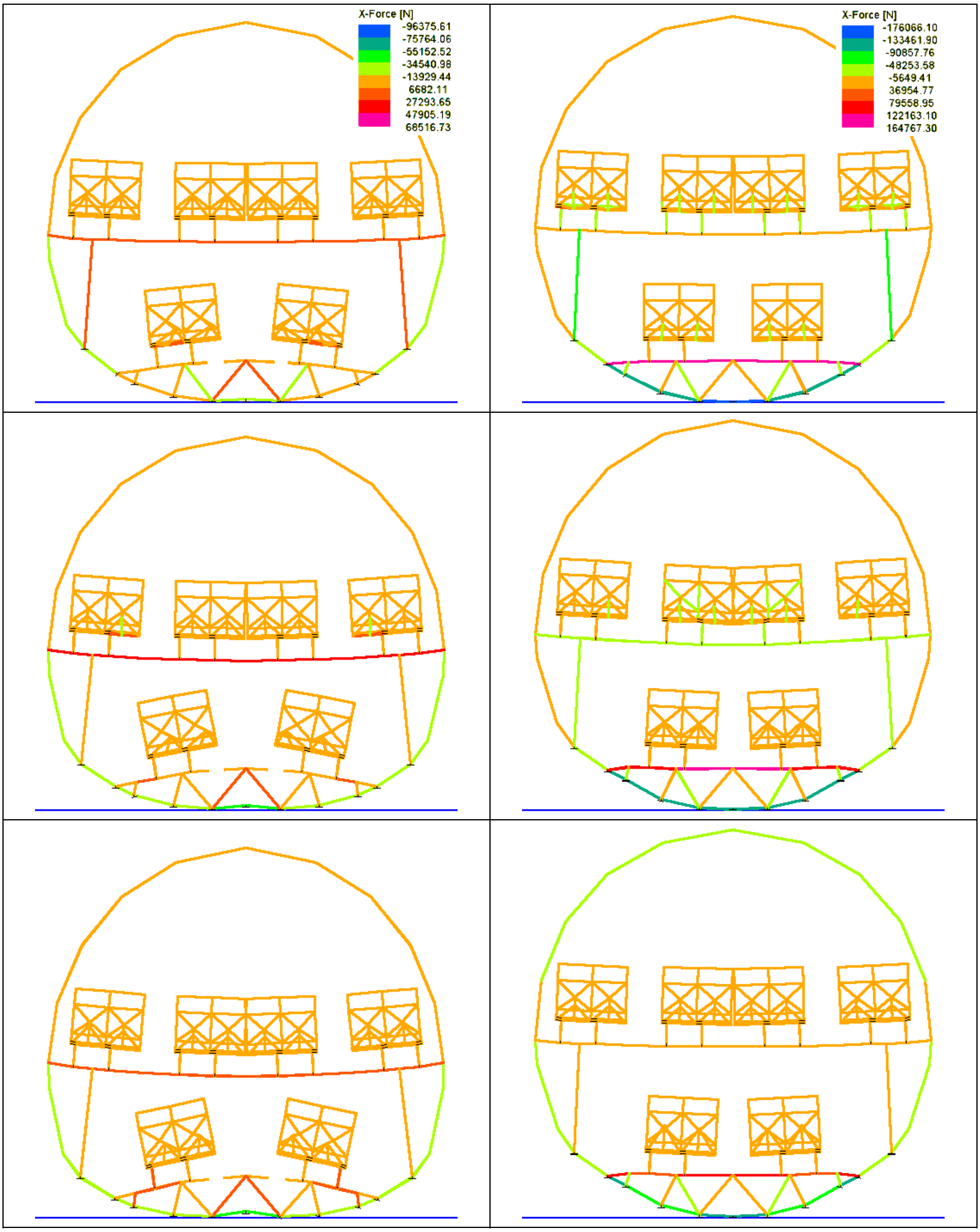
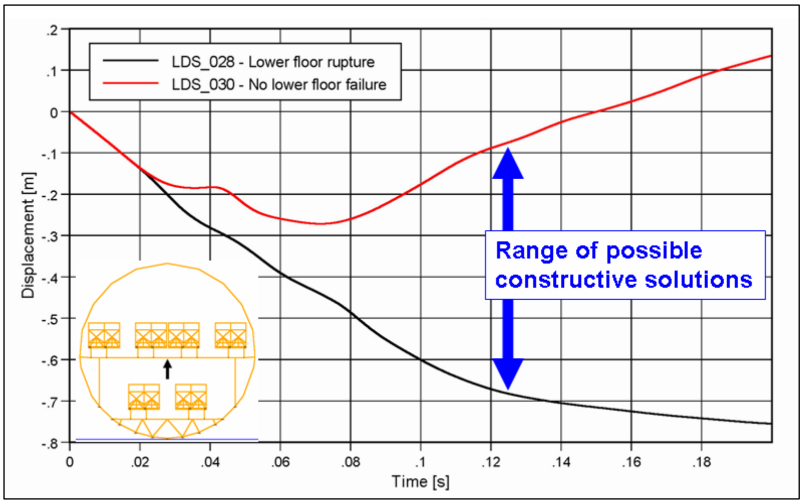


Fig. 6: Comparison of 2 LDS configurations, Times = 50, 80, 100 ms / KAP [10]

It can be seen that the loading of the structure is much higher in configuration LDS_030 (re-inforced cross beams) whereas the deformation is considerably reduced. The comparison of the displacements in the following diagram confirms these differences.



After 70 ms the 'stiffened' configuration rebounds, whereas the 'basic' configuration is still moving downwards. All realizable designs will be between these two curves.

Fig. 7: Vertical displacement of floor centre (main deck) in two configurations.

In the following two diagrams the occupant accelerations are shown for 3 different seat positions – two on the main deck and one on the lower deck. In the 'basic' configuration (LDS_028), the highest accelerations occur at the lower deck seat and the lowest level can be found for the centre seat on the main deck.

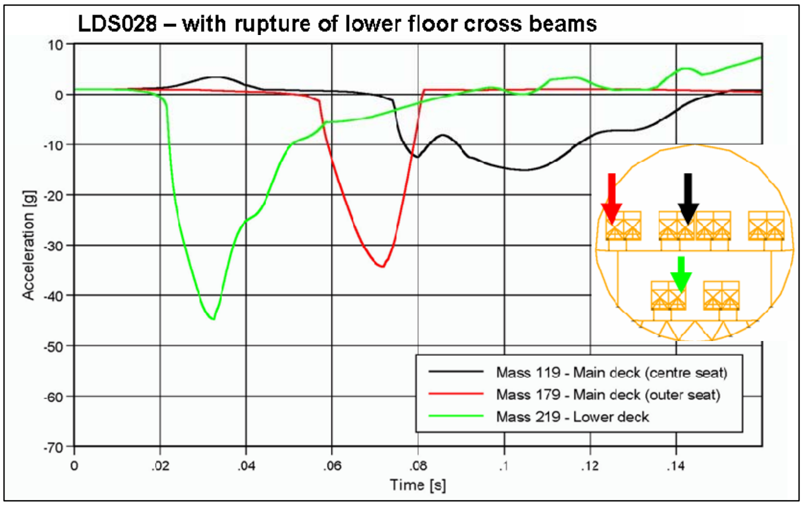
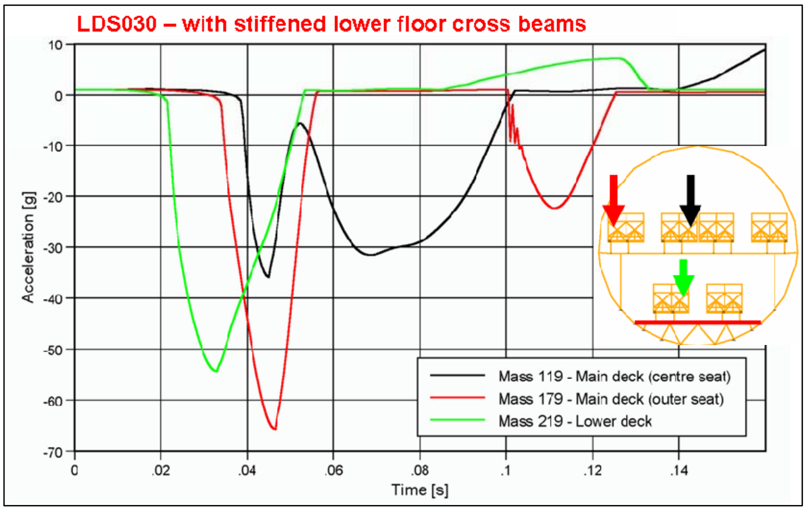


Fig. 8: Comparison of z-accelerations at 3 seat positions (LDS_028).



The configuration with the stiffened LD floor cross beams (LDS_030) generates much higher accelerations for <u>all seat positions</u>. The lowest acceleration level can again be found for the main deck centre seat, but now the highest accelerations do not occur on the lower deck but at the outer seat on the main deck.

Fig. 9: Comparison of z-accelerations at 3 seat positions (LDS_030).

Apart from securing a survival space in the lower deck area, a configuration with stiff, reinforced lower deck floor cross beams does only generate disadvantages.

4 Assessment of occupant safety in different LDS Configurations => BASE Criteria

In order to compare the results of an extensive parametric study and to identify the best design, a method was developed which assesses the occupant safety in each of the nearly 200 different simulated configurations – the BASE criteria.

The safety potential of each LDS configuration (and each seat) is judged on the basis of a point scheme, which assesses the following 4 criteria: Accelerations, preservation of a living space, injury risk from falling objects (e.g. overhead bins or hand luggage) and preservation of an escape route. The evaluation scheme thus includes the entire occupant environment.

BASE – Criteria	
Overhead Bin	150 points
Acceleration	500 points
Survival Space	250 points
Escape Route	100 points
Maximum achievable: 1000 points	

Fig. 10: BASE Criteria – Distribution of points.

Remark: The BASE Criteria are used to <u>compare</u> different configurations and seat positions, not to give an exact "safety mark" or to predict a certain injury level!

Of course, the weighting of each criterion in such a scheme is always debatable. Unfortunately, it will never be possible to define these shares exactly.

In the here presented work, the distribution of points was based on the evaluation of accident statistics. Figure 11 shows some results of the NTSB Study "Survivability of Accidents Involving Part 121 U.S. Air Carrier Operations, 1983 through 2000" [5]. The two graphs show the distribution of the causes of death in all technically survivable accidents and in all serious accidents which includes the unsurvivable accidents.

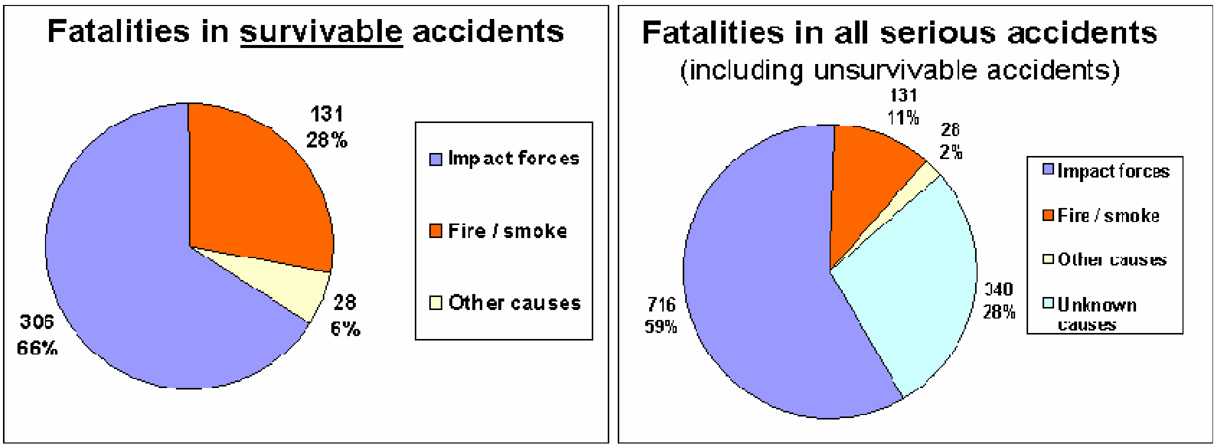


Fig. 11: Fatalities in survivable / unsurvivable accidents, source: NTSB [5]

The second diagram indicates an 11% share for fire and smoke related causes of death. The risk of fire/smoke cannot be calculated with a crash simulation code like DRI-KRASH. But, as fire and smoke normally occur after the impact, this risk can partly be linked to the existence of an escape route and is thus considered in the BASE criterion 'Escape Route'.

Subsequently, the 4 BASE criteria are explained in more detail.

4.1 BASE Criterion 'Acceleration' (50%)

Out of the 4 BASE criteria, the acceleration criterion is the most important one. It includes all occurrences which are related to the accelerations acting on the occupant, e.g. the risk of spinal injury or the failure (breaking away) of the seat.
Depending on the capabilities of the used simulation tool, this criterion may also be divided into different sub-criteria, e.g. the use of the Dynamic Response Index (DRI) – as it is calculated within the program DRI-KRASH – or the lumbar spine load criterion.

EIBAND evaluation of acceleration pulses

In the here presented work, a modified EIBAND approach was used for the evaluation of the occupant accelerations.
Besides the minimum and maximum accelerations, the duration of a certain acceleration level must be known in order to judge an occupant's acceleration pulse with regard to the risk of injuries. Nearly 50 years ago Martin Eiband (NASA) developed the EIBAND diagrams [6]. These diagrams depict the magnitude of the acceleration versus the duration of uniform acceleration plotted on a logarithmic scale and are used in order to ascertain the probability of crash survivability and the extensiveness of the injury to passengers. The Eiband curves are based on experimental results: If acceleration pulses lie beneath the lower curve, it can be presumed that injuries will be of a minor nature; between this lower and the higher curve, moderate injuries can be expected and if acceleration pulses lie beyond the upper Eiband curve, injuries are assumed to be severe (Figure 12).

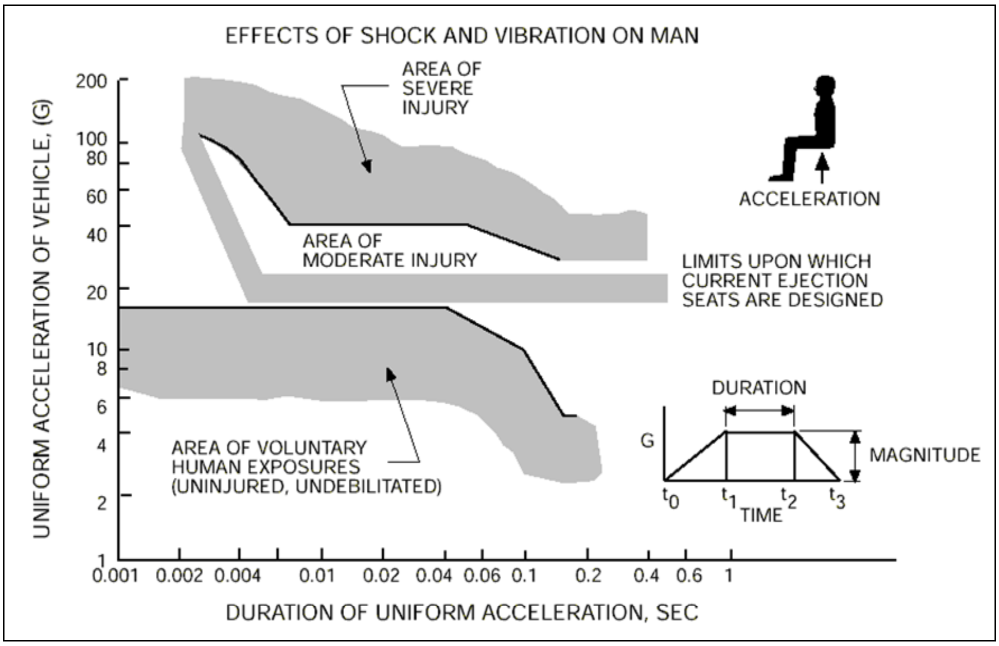
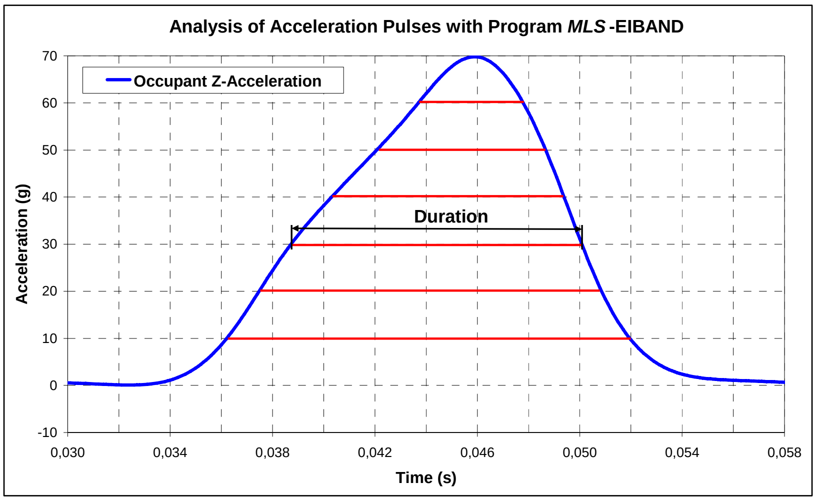


Fig. 12: EIBAND diagram for vertical accelerations [6].

In order to obtain information about the probability of injury for the simulated configurations in the lower deck seating study, it was necessary to evaluate the pulses with regard to the duration of each acceleration level. For this purpose the ***MLS*** EIBAND tool [7] was used which analyses a given acceleration pulse.



It calculates the duration of uniform acceleration for each acceleration level. The program starts the calculations at a level of 1 g and repeats the calculation for every level up to the maximum acceleration at a user-defined acceleration increment. With MLS EIBAND, it is also possible to select only a part of the pulse (with minimum and maximum times).

Fig. 13: Evaluation of acceleration pulses with MLS EIBAND [7].

Remark: The Eiband curves were not developed with the type (and shape) of acceleration pulses occurring in the simulations with the fuselage section KRASH models. Therefore, the method of evaluating the pulses which is used here can only give qualitative results. An exact value for the probability of injuries can not be specified. Nevertheless, regions with higher and lower risk can be located by comparison of the results for different passenger positions.

The following figure shows how the occupant accelerations at 6 different seat positions are represented in the EIBAND diagram. In this sample, the curves of 3 seats reach into the area with severe injuries, the centre seat positions on the main deck have the lowest injury risk.

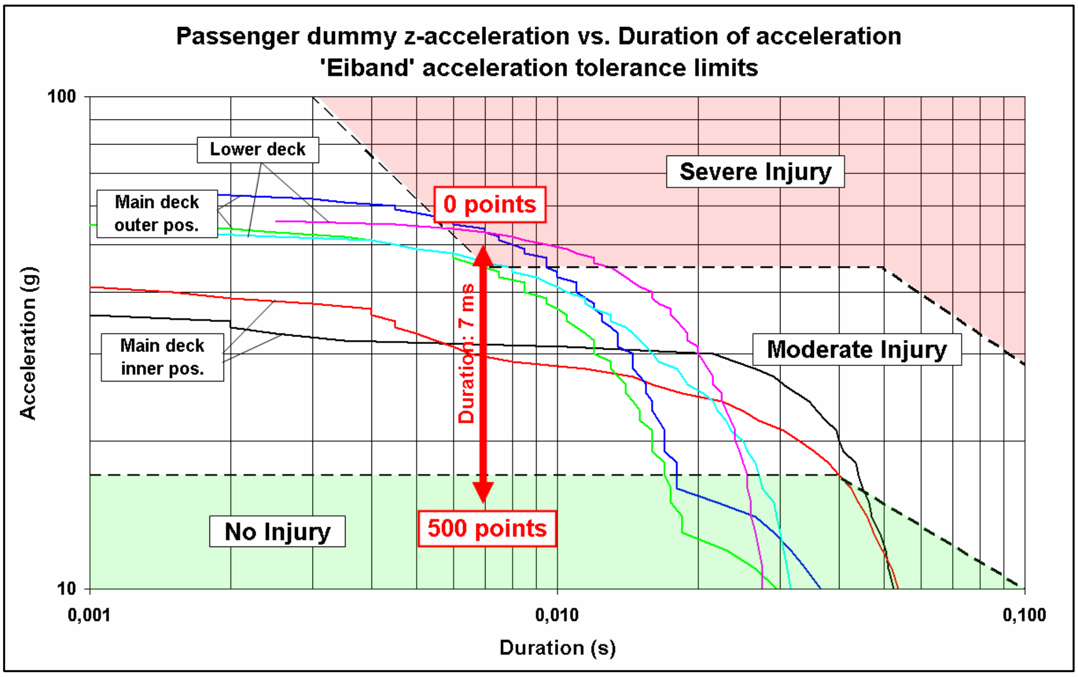


Fig. 14: Representation of occupant accelerations in EIBAND diagram.

In the next step, the results of the EIBAND evaluation must be assigned to BASE criteria points. For the cases simulated in this study, the highest probability of reaching the area with severe injuries is in the region with an acceleration duration of 7 ms (sharp bend in the Ei-band curve that separates the areas of moderate and severe injuries). Therefore, the 7ms duration of acceleration was defined as the significant value.

Figure 15 shows how the 7ms accelerations are mapped to BASE criteria points (<15 g: 500 points, >50 g: 0 points).

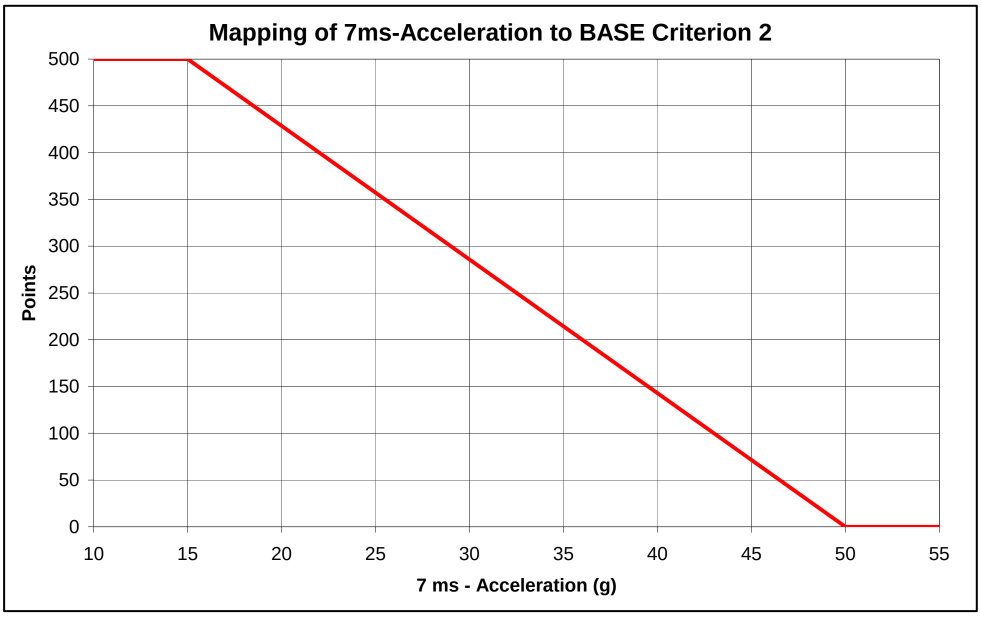


Fig. 15: Mapping of the 7ms-Acceleration to BASE criteria points.

4.2 BASE Criterion 'Survival Space' (25%)

The 'survival space' was defined as the second most important BASE criterion. Here, a relatively simple method was used to measure this space. As a result of the crash kinematics, the largest differences of the lower deck cabin height occur for the position in the centre. Therefore, the change of the distance between the two floors is taken as the characteristic dimension.

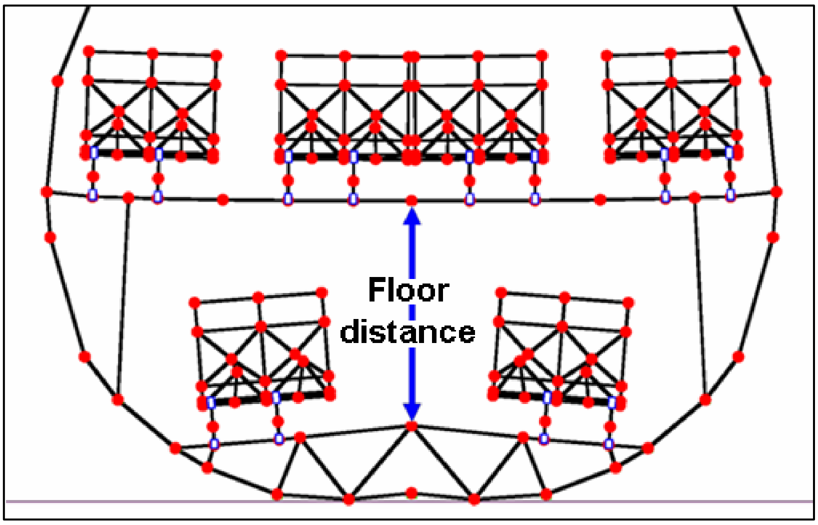


Fig. 16: Characteristic 'survival space' dimension.

Figure 17 shows how the reduction of the floor distance is mapped to BASE criteria points (<50 mm: 250 points, >600 mm: 0 points). Of course, it cannot be said that a reduction of 600 mm leaves no survival space. But the experience – simulations of different aircraft models with different crash simulation programs (also FE type) – showed that such a large deformation is normally equivalent of the total collapse of larger structural parts (e.g. the main deck floor support struts or parts of the main deck floor itself).

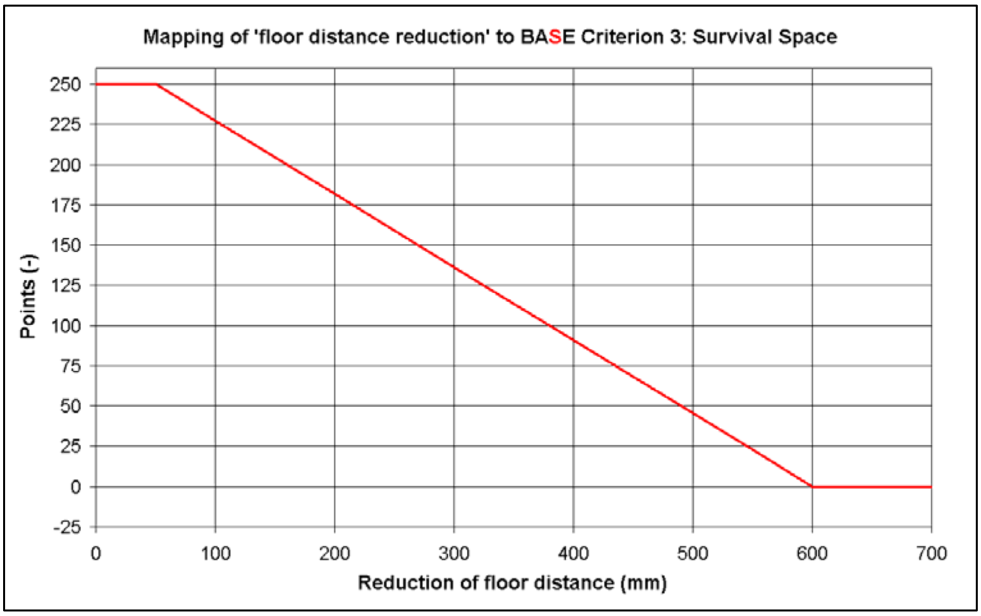


Fig. 17: Mapping of the floor distance reduction to BASE criteria points.

4.3 BASE Criterion 'Luggage Bin' (15%)

From aircraft accidents and also from different tests it is known that the luggage in the overhead bins can turn out to be an injury risk for the occupants. The luggage can fall out of the bins or the complete overhead bin may even come down.
In the here presented study, each seat position is judged according to the probability that luggage or bins can harm the occupant. As a sub-criterion the loads on the bins could be evaluated for each simulated case. The maximum number of points (150) is given for seating configurations in which no luggage bin is positioned over the head of the occupant.

Fig. 18: Failure of overhead luggage bins in test / accident; Source: FAA [8], AAIB [9]

4.4 BASE Criterion 'Escape Route' (10%)

The fuselage deformation during the crash has different effects on the aisle width of the two decks. On the main deck, the aisle width is reduced, whereas on the lower deck the aisle width is increased (Figures 19, 20). In the evaluation of the parametric study, each seat location is judged according to the size of the remaining aisle width. Furthermore, the position relative to the aisle is considered: An aisle seat gets more points than a window seat.

Fig. 19: Change of aisle width during a crash test.

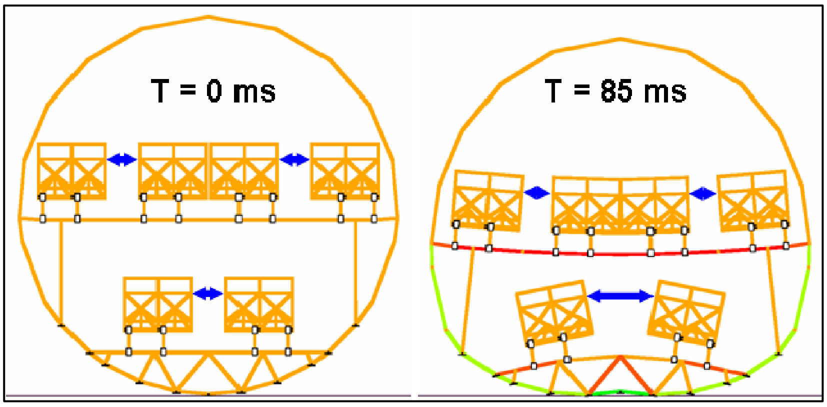


Fig. 20: Crash kinematics – change of aisle width.

4.5 BASE Criteria: Overall results of the parametric study

The results of the BASE criteria evaluation of the LDS parametric study are summed up in the following table. For each of the 6 different seat positions the sum of the points out of the 4 criteria is given.

Each configuration is then judged according to the seat with the lowest result (not according to the average of the 6 seats). The best result is achieved for configuration 148 which will be described in detail in the following chapter. For this configuration, the occupant safety level reaches approximately 85% of the main deck level (basis of comparison: seat 4 in the original basic configuration).

The table also shows that the critical seat (marked in red) is not in every case on the lower deck. For some configurations it is Seat 4 (the outer seat on the main deck).

Con-figuration	Seat 1	Seat 2	Seat 3	Seat 4	Seat 5	Seat 6	Average	Min. value (out of 6)
148	787	767	659	597	**536**	545	648	**536**
133	677	767	667	604	**532**	631	646	**532**
140	711	777	671	601	**517**	596	646	**517**
152	753	724	590	521	**510**	520	603	**510**
151	810	830	751	691	**509**	566	693	**509**
143	726	787	664	594	**507**	587	644	**507**
145	621	651	549	**499**	613	589	587	**499**
128	799	830	736	723	**490**	587	694	**490**
45	600	626	519	**479**	566	531	553	**479**
48	781	751	641	586	501	**478**	623	**478**
149	727	669	543	**467**	533	499	573	**467**
142	780	827	823	757	**464**	592	**707**	**464**
139	779	823	793	754	**461**	619	705	**461**
33	667	756	629	543	**440**	556	598	**440**
49	721	657	516	443	449	**439**	537	**439**

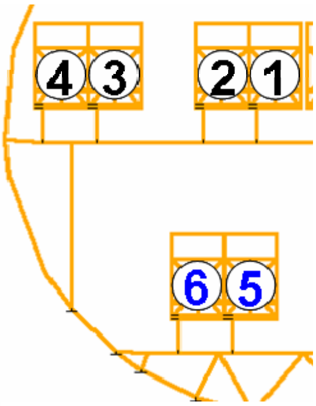


Fig. 21: Overall results of parametric study.

5 Proposed LDS Configuration

Figure 22 shows some of the features of the configuration with the highest rating in the Lower Deck Seating study: Two double seats are used which have an aisle between them with twice the standard width. Moving the LD seats further outwards reduces the accelerations on the LD passengers and provides a better escape route. This arrangement has also some advantages in the 'normal' aircraft operation as the passengers can enter and leave the airplane much faster and the service can be carried out without blocking the aisle.

In the proposed configuration, the double aisle width is also necessary as an additional central strut is used to secure the survival space and to absorb part of the impact energy. Variations of the strut properties showed that these additional struts between the floors must not be 'stiff' like the standard passenger floor struts, as such a design would increase the accelerations on both floors. A reduction of the distance between the two floors (during the crash) has to be allowed and energy absorbing elements have to be included in these extra struts.

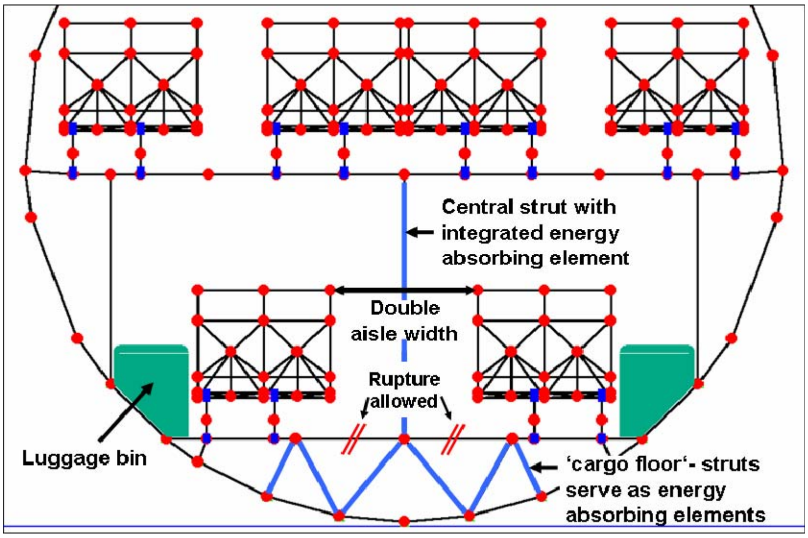


Fig. 22: Proposed LDS configuration.

The struts below the lower deck floor are also designed as energy absorbers.

The luggage bins are placed in the outer area of the lower deck (attached to the LD floor and frame). This concept also offers some advantages in the standard aircraft operation as the LD passengers have access to their luggage during the flight without leaving their seats. The top of the bins can also be used as additional "tables" during the flight.

Figure 23 shows the earlier described EIBAND diagram for the proposed lower deck seating configuration. It can be seen that all seat positions on the main and lower deck are in the 'moderate injury' area.

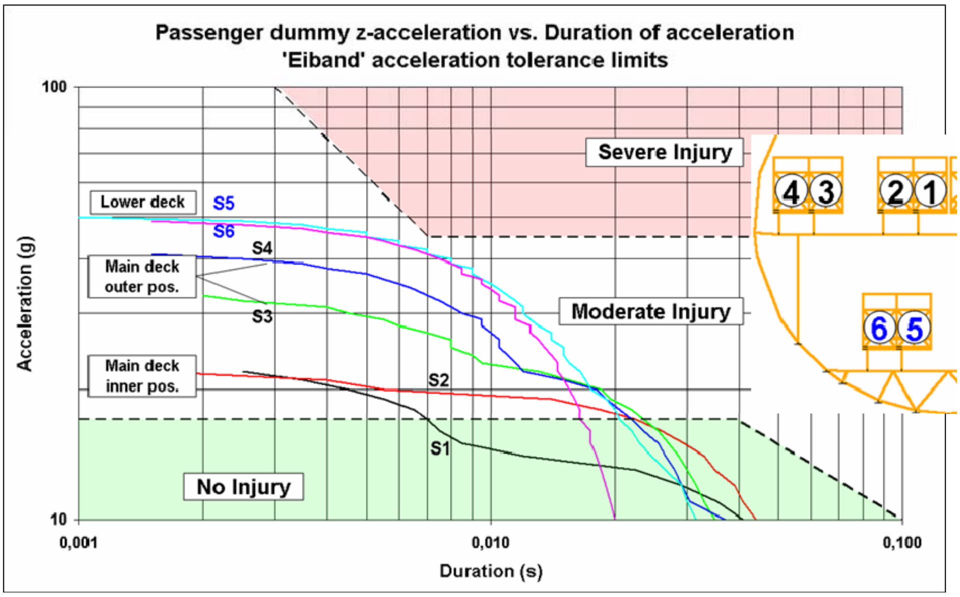


Fig. 23: 'Eiband' diagram for the proposed LDS configuration.

In Figure 24, the deformation and loading of the fuselage (in configuration 148) is shown together with the acceleration, velocity and displacement time histories which were calculated for the centre of gravity of the DRI-KRASH model.

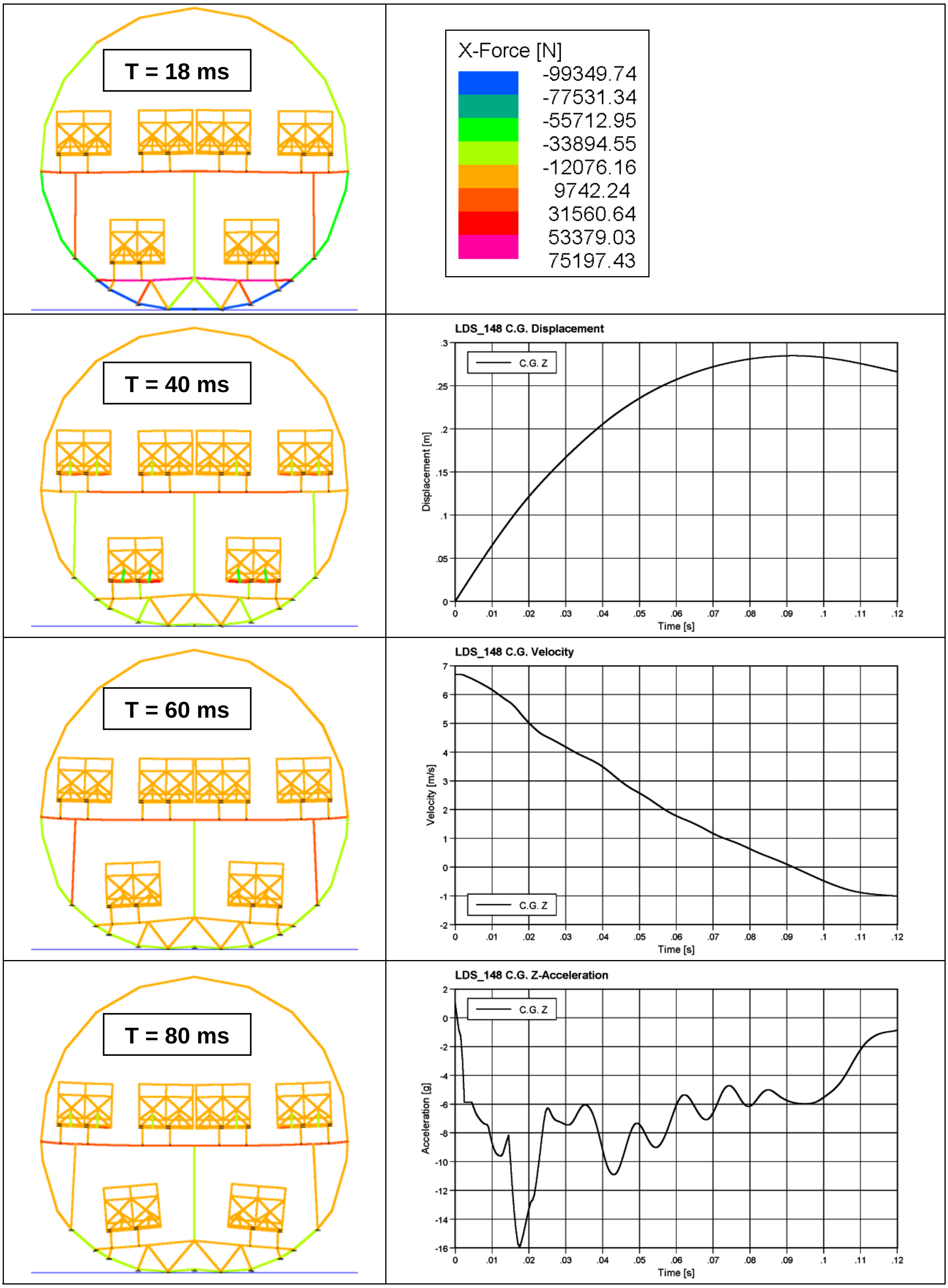


Fig. 24: KRASH sequence / CG time histories – LDS configuration 148.

6 Guidelines for the realization of Lower Deck Seating

- In order to secure the survival space for the occupants in the lower deck area, additional struts should be used (between lower and main deck).
- These additional struts between the floors must not be 'stiff' like the standard passenger floor struts as such a design would increase the accelerations on both floors.
- These extra struts must include energy absorbing elements (a reduction of the distance between the two floors has to be allowed).
- The 'cargo floor'- struts should also be designed as energy absorbing elements.
- Moving the LD seats further outwards (increasing the aisle width) reduces the accelerations on the LD passengers and provides a better escape route (has also advantages in the 'normal' aircraft operation).
- Luggage bins should not be attached to the main deck floor cross beams but placed in the outer area of the lower deck (attached to the LD floor).

7 Conclusions and Outlook

- Different DRI-KRASH models of a wide-body fuselage section, the seats and the occupants were set up in a parametric way.
- The BASE Criteria were established for the comparison of occupant safety in the different Lower Deck Seating (LDS) configurations.
- Crash simulation calculations with numerous configurations were carried out in an extensive parametric study and in each case evaluated according to the presented BASE criteria.
- DRI-KRASH proved to be an excellent tool for doing a wide range of parametric studies in a relatively short time.
- A configuration was chosen where the occupant safety level reaches approximately 85% of the main deck level.
- Further improvements are required and seem to be feasible.
- The here developed LDS design rules could contribute to a possible future use of the cargo compartment as additional passenger cabin.

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