Crashworthiness Review for Electric Vertical Take-Off and Landing Vehicles and Implementation of the Automotive Safety Approach

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ABSTRACT: Due to operation in urban areas, air taxis compete, unlike most conventional aircraft, with individual transportation systems like cars and public transportation systems. Safety and comfort are important for potential air taxi customers. This work highlights the importance of eVTOL's crashworthiness and introduces a development and evaluation approach. It is done by deriving eVTOL-specific full-vehicle crash load cases analogue to the automotive approach and introducing a corresponding crashworthy design concept, using an analytical approach supplemented by a multi-body-dynamic simulation. The multi-body-dynamic simulation confirms that the analytically developed crash concept fulfills the previously derived crash load case's test criteria. In contrast, the simulation demonstrated that lumbar loads could exceed certification limits for an advanced crash load case with higher impact velocity.

KEYWORDS: eVTOL crashworthiness, safety, automotive safety approach, full-vehicle crash test

1. Introduction

The increasing energy density of high voltage batteries and further development progress in connectivity and digitization enables new vehicle concepts such as electrical vertical take-off and landing vehicles (eVTOL). The eVTOL industry is growing rapidly; according to Roland Berger's study [1], more than 160.000 units will be part of air traffic by 2050. First services are announced for the Olympic Games in 2024. [2]

The industry is well aware of the lack of crashworthiness for the rising eVTOL mass market. NASA initiated 2021 a crashworthiness workshop to address this challenge. Publications of the DLR [3] and NIAR [4] highlight the need for further research regarding the integration of crashworthiness during the development process of eVTOL and the emergency landing condition standards. Novel propulsion and control systems, including high energy density batteries, create unknowns about post-crash risks, and novel vehicle architectures, seating arrangements, and urban environment operations may need novel safety concepts. Both [3] and [4] recommend implementing safety from the conceptual design stage and investigating the influences of novel aspects using simulation methods. Lowell Foster from GAMA [5] suggests planning on accidents and adapting the automotive industry approach. More about the automotive industry approach, here also referred to as the automotive safety approach, will be explained in section 2. Justin Little and Joseph Pellettiere from NASA/FAA [6] presented a full-vehicle crash test simulation to gain data and knowledge about the crashworthy performance of urban air mobility (UAM) vehicles and simulation capabilities.

2. Crash Safety

While aviation's crash safety approach mainly focuses on active safety (crash prevention), the automotive safety approach often prioritizes passive safety (crash mitigation), aiming for uninjured occupants in crash events. One key action to ensure and evaluate occupant protection via passive safety has been establishing standardised full-vehicle crash tests. Nowadays, full-vehicle crash tests are conducted by governmental organizations, private organizations, and vehicle manufacturers to evaluate legal, consumer protection, or manufacturer-specific requirements. All tests are based on fundamental accident research, assessing the risk, and probability of occurrence vs. severity, including fatality.

2.1 Vehicle Measures

eVTOL are similar to helicopters in many ways but have distinct differences in technical aspects. Most manufacturers state that the safety of their eVTOL is ensured by a redundant flight system design. Redundancy of the flight system enables that even a failure of one or several rotors does not lead to a crash, and the vehicle can still perform a controlled landing. Another widely used safety feature on eVTOL is the accommodation of an emergency parachute system. Unlike helicopters, whose design, with a rotor located centrally above the fuselage, make installing an emergency parachute system difficult, the installation on eVTOL is less problematic, albeit increasing weight. Short take-off or at least landing (STOL) capability is another safety feature of some eVTOL with the possibility to perform conventional landing manoeuvres. The prerequisite is the presence of wings that generate sufficient lift, as well as a landing gear to enable rolling touchdowns. Information about passive safety measures concerning the structure or used materials is not yet published for the existing eVTOL concepts. However, it is expected that eVTOL's crashworthiness will be based on a mix of requirements for helicopters and small airplanes, as EASA's recent publications for VTOL certification (SC-VTOL [7, 8] & Means of Compliance [9–12]) point out.

Due to the lack of eVTOL's structural crashworthiness design concepts, the following section is a short review of relevant automotive crash design structures.

In automotive design, crash load requirements are a decisive development criterion. Early in the development phase, the crash concept, including the load paths and force levels, is defined. One essential function of the vehicle's body structure is the protection of the occupants. A common structural approach to protect the occupants is a rigid life-cell around the occupants supplemented by energy-absorbing structures for the conversion of the kinetic impact energy. The life-cell is built by A-, B-, and C-Pillar connected with stiff roof and floor cross member. For front- and rear impacts, the main energy is absorbed by two longitudinal members, which run into the rocket panels and centre tunnel. [13] In racing situations, such as Formula One, drivers frequently survive extremely high crash loadings where cars use a monocoque design made of laminated composite sandwich materials. The outer layers are made of carbon fibre reinforced polymer (CFRP), which encloses a honeycomb structure in the core. The force level can be specifically adapted to the requirements via targeted material thickening. Additionally, Formula One cars use designs tailored to the single driver/occupant such as the "Halo" and a nose cone section for frontal impact protection.

3. Crash Impact Conditions

To develop appropriate passive safety systems, crash impact conditions must be identified. Therefore, accident events and causes are categorized to identify relevant crash scenarios and impact conditions. Future eVTOL accident events can be determined by two approaches. First, investigation of relevant air- and rotorcraft data and statistics, for example, commercially used small airplanes and helicopters, and second, approximations and predictions of accident events. These can be based on aviation accident data, (technical) failure modes, and -rates, but also on future eVTOL mission analysis and simulations.

Analysis of aviation accident events shows that the most frequent fatal crash scenarios result from loss of control - in flight (LOC-I), controlled flight into terrain (CFIT), and runway excursion (RE). Further categories are system/component failure or malfunction (SCF), abnormal runway contact (ARC), and undershoot/overshoot (USOS). [14–16] One of the main references for aviation accident analysis is the 1985 published DOT/FAA/CT-85 study [17] of the FAA, where 311 U.S. civil helicopter accidents from 1974 until 1978 were analysed regarding impact conditions and occupant injuries. The study identifies six crash scenarios: Vertical impact, longitudinal impact, rollover, wire strike, water impact, and high yaw rate impact. The vertical crash scenario was determined as the most hazardous. Engine failure or malfunction is, with 27 % of the 311 accidents, the most frequent accident cause. The study also represents the base of EASA's recently published certification proposal (SC-VTOL [7, 8] & Means of Compliance [9–12]) for future eVTOL in terms of crash requirements. The certification proposal prescribes a *minor emergency crash landing*, which requests loads below 30 g at seat attachment level after a vertical impact velocity of 9,1 m/s, which covers slightly more than 95 % of the 311 survivable helicopter accidents. The requirement is also already known from helicopter certifications (CS-23.562 [18], CS-27.562 [19], CS-29.562 [20]).

Analysing eVTOL missions, one of the most critical phases will occur during the transition phase from hover to cruise mode. Three main reasons are; the complex and undiscovered transition of lift mechanisms, the absence of kinetic energy in the vehicle system to operate a safe emergency landing, and altitudes below minimum altitudes for the safe activation of ballistic recovery systems [3, p. 5]. At the time of article writing, only a few aircraft are on the market that show transition phases, which is why data about the transition phase's risk and resulting impact conditions is rarely available. Another critical phase will be the vertical take-off and landing phase, according to aviation accident statistics. [21, p. 42] This is a flight phase, where passive safety shows high efficiency in terms of weight and economic aspects vs. safety benefits due to relatively low velocities compared to in-flight velocities.

Furthermore, low flight heights (300 – 500 m) cause a reduced reaction time to initiate an emergency landing and navigate to appropriate ground conditions.

The expansion of urban air mobility will increase the density of aviation vehicles in cities. This entails two significant safety risks; mid-air collisions, particularly during cruise mode, and emergency landings, with differing ground conditions from hard or soft soil.

In conclusion, e*ngine failure and malfunction* are the most frequent accident cause and are expected to rise, caused by the novelty of the technology [12, p. 5]. The most critical flight phases are the *transition* and *take-off and landing* phases. Vertical impacts are the most hazardous crash scenarios. Additionally, a rising quantity of vertical *take-off and landing* operations are expected for the UAM market with short-distance flights. Vertical crash impact conditions are therefore considered to be the most crucial crash scenarios and will be the focus of this work.

Vertical impact velocities differ for civil, navy, and army helicopters between 8 m/s and 13 m/s covering 95 % of accident events according to [22]. In the following work, simplified crash impact conditions with two levels of vertical velocity are defined. Vertical crash 1 (VC 1), with a velocity of 10 m/s, which is slightly higher than current certification requirements, and a vertical crash 2 (VC 2), with a velocity of 15 m/s, covering 99 % of the in DOT/FAA/CT85/11 study [17] investigated helicopter accidents. (Figure 1) The crash impact conditions claim no general validity and do not consider roll, pitch, or yaw angle variations. Impact angles ranged between -5° up to +15° for pitch and +/-10° for roll angles, according to [23]. It is expected that control units will improve and be capable of keeping the vehicle, in most cases, in a level attitude with low longitudinal and lateral velocities. Longitudinal and lateral velocities are therefore expected to be very low and are not considered in this crash configuration. The crash scenario covers particularly accidents resulting from complications during the start- and landing phase, with the vehicle hovering.

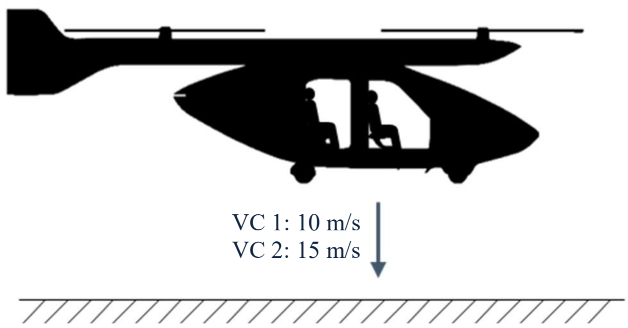

Figure 1. Expected most important eVTOL crash impact condition - vertical crash

3.1 Requirements

To evaluate the system's crashworthiness, load cases and criteria are reviewed and defined.

Biomechanical load limits are used to assess and specify the consequences of a crash on occupants. Injuries are not only dependent on maximum achieved acceleration but also on the direction of action and the duration of the load. Even though biomechanical load limits can vary widely [24], in this approach, regulation requirements [11] and in-house definitions regarding accelerations and forces are used to evaluate crashworthiness. With a focus on vertical impacts, the most critical load occurs in the axial direction of the lumbar spine. [25] According to EASA's certification regulations [11], the maximum lumbar load is required to be lower than 6674 Newton. The Eiband diagram (Figure 2) represents the basis for vertical acceleration evaluation. It shows an expected injury level depending on the acceleration value over the duration based on voluntary human exposures and animal experiments with hogs and chimpanzees.

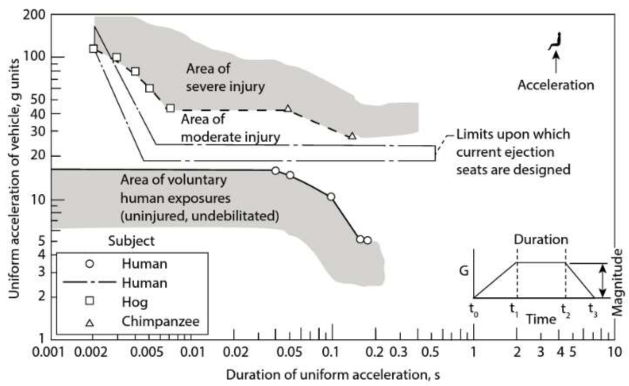

Figure 2. Biomechanical acceleration limits in vertical direction – Eiband-diagram [26, 27]

In addition to the crash load cases, legal regulations [28] for landing gear design must be considered. Two tests are established, the *limit drop test* (LDT) and the *reserve energy absorption drop test* (READT). In the former, the vehicle drops to the ground from a height of 0.33 m. In the reserve energy absorption drop test, a vehicle drop from 0.495 m is prescribed, and landing gear failure is not permitted. Failure is defined by the fact that, excluding the landing gear itself, no structures of the vehicle are allowed to touch the ground. For the LDT, a maximum occupant acceleration of 2 g is inhouse defined, while for the READT, 4 g is expected to be appropriate. For all load cases, the occupant's acceleration is interpreted using the Eiband-diagram, and the limit of the lumbar load is set to 6674 N.

Furthermore, energy absorbing structures have to collapse in a controlled deformation sequence. Deformations should take place from the outside to the inside of the vehicle, excluding the seat console and airbag.

shows an overview of the to-be-considered load cases, their characteristics, and criteria.

Table 1. Load-Case Overview - Characteristics and Criteria

Load-Case	Impact Velocity	Impact Mass	Criteria
LDT	2,54 m/s	3000 kg	Acceleration in vertical direction $a_v < 2g$; No plastic deformation.
READT	3,12 m/s	3000 kg	Acceleration in vertical direction $a_v < 4g$; No contact between underbody and ground.
VC 1 – Low Speed	10 m/s	1200 kg	Acceleration in vertical direction in area of moderate injury based on Eiband-diagram; Max. axial lumbar load F < 6674 N
VC 2 – High Speed	15 m/s	1200 kg	

4. Crashworthy Design Concept

The crash concept base is a rigid life-cell and energy absorbing structure. In the first conceptual crash design concept for eVTOL, a reduced mechanical system of four energy-absorbing systems is considered (see Figure 3). An *airbag*, deployed below the underbody, a *landing gear*, potentially interacting with the airbag, and a *seat console*. Between the seat console and the airbag is a further energy absorbing structure defined as *passive structure*.

The flight propulsion unit (FPU), including the wings, is assumed to be capable of decoupling from the people transport unit (PTU) via a predefined breaking point just before impacting the ground. Detailed construction limitations and principles are not the focus of this work and are not considered here.

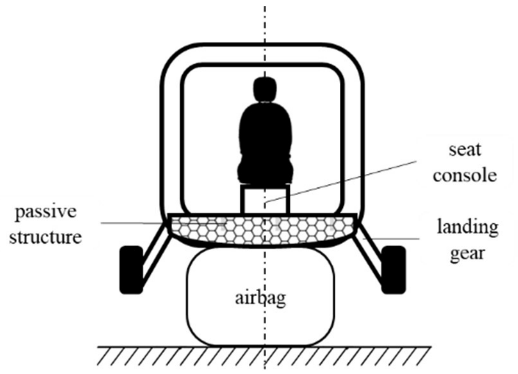

Figure 3. Abstract illustration of energy absorbing systems in vertical crash load case.

The complex technical system is reduced into a simplified mass-spring-damper model for a better understanding of following investigations. Figure 4 shows the significant representative masses of the four passengers, seats, the vehicle structure, the landing gear, and the energy absorbing systems in the form of spring-damper symbols for the seat console, the passive structure, the landing gear, and the airbag. The variable $x_{1...5}(t)$ represents the displacement dependable on time for each mass.

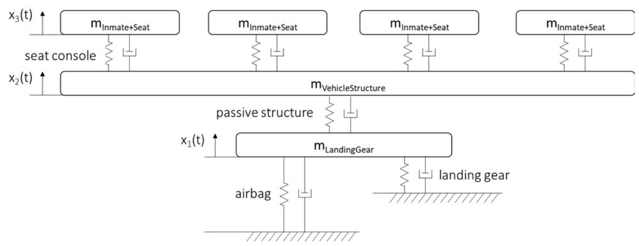

Figure 4: Mass-spring-damper model for a crashworthy eVTOL design concept with respect to vertical impacts

4.1 Design of Energy Absorbing Systems

With known vehicle mass and impact velocity, the to-be-absorbed energy can be identified for the reduced mechanical system as the whole kinetic energy of the vehicle. For simplification reasons, all energy absorbing systems are assumed to have a constant force over displacement characteristic. Based on required deformation lengths, first, the force level of the landing gear is calculated using the energy conservation law with respect to load case READT. Since the absorbed energy of the landing gear is defined by the READT load case, the force levels of the airbag and passive structure can be designed based on the remaining kinetic energy. This kinetic energy is split up with respect to the deformation length of the respective energy absorption systems to reach a global constant force level. Afterward, the force level of the airbag is lowered by 10 %, and the passive structures are enlarged by 10 % to achieve the aimed deformation sequence (Figure 5). Occurring accelerations can be derived from the force levels of the main absorbing systems for designing the required force level of the seat consoles. All system force levels are below 300 kN and realistic with respect to constructive implementation. The following section is a plausibility check for all four crash systems.

Airbags: According to [29], 100 kPa is a realisable pressure level for airbags. This is also mechanically plausible considering that the atmospheric pressure is about 100 kPa, and Newton's 3^{rd} law (action is equal to reaction) applies. Automotive driver airbags typically have a volume of about 80 up to 150 litres [30]. Equal airbag volumes are possible for eVTOL with four airbags below the vehicle's underbody, considering an underbody area of about 1 m^2. The analytically calculated force level is 100 kN and can be influenced by inertial pressure controlled via gas charge or venting holes and the effective airbag area.

Landing gear: The front landing gear is designed as a shock absorber. Therefore, the force over displacement characteristic can be well controlled. [31] The rear landing gear could be approximated as a cantilever beam in a reduced mechanical system, assuming a linear force-over-displacement performance. Both, the front and rear landing gear are in this work considered as one system with a corresponding constant force level of 100 kN.

Passive structure: To realize a constant force level with high energy absorbing efficiency, the passive structure is designed with aluminium honeycombs. According to aluminium honeycomb's datasheets [32], requested force levels between 120 and 300 kN can be realized by choosing a crush strength considering the effective area. For force levels between 100 up to 300 kN corresponding honeycomb characteristics are available. [33]

Seat console: With a spring damper system integrated into the seat's back, the deformation characteristic can be set. A force level of 10 kN is realistic, according to [34].

In conclusion, the force level of seat consoles is driven by the spinal load limit. The landing gear's force level is conditioned by the certification specification load case (READT). The force level of the passive structure in the underbody and the airbag can be varied but must consider typical force over displacement courses and simplified constructive implementation restrictions.

These analytical calculations and preliminary considerations are the base of the following mathematical optimization.

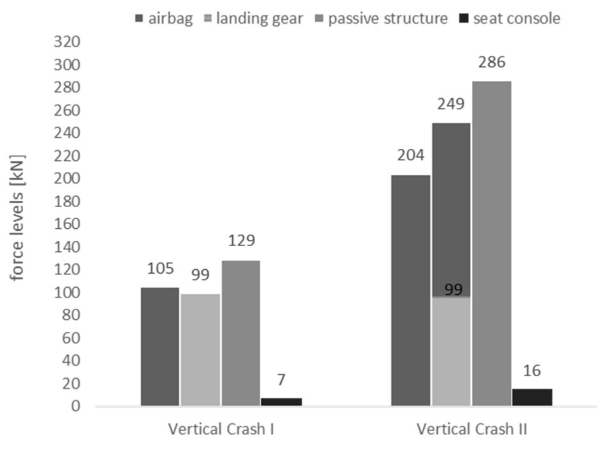

Figure 5. Force levels for energy absorbing systems after analytical design - vertical crash 1 & 2

To find the lowest lumbar loads and corresponding crash system force levels, the mathematical approximation optimization *adaptive response surface method (ARSM)* [35] is used. The optimization process varies the analytically determined crash system forces in the limits of +/- 25 %, aiming to minimize the dummy's accelerations for each load case. Optimized force levels are shown in Figure 6.

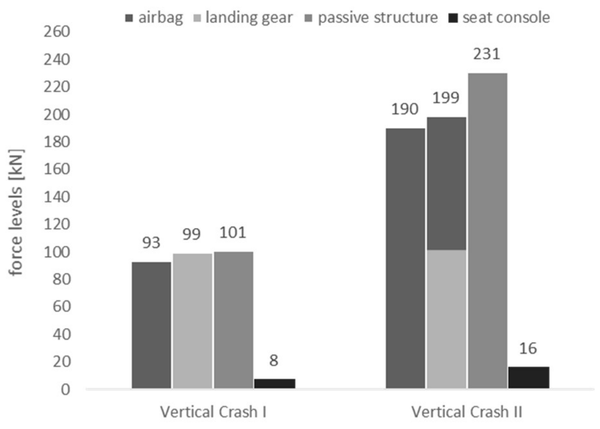

Figure 6. Force levels for energy absorbing systems after mathematical optimization - vertical crash 1 & 2

4.2 Multibody Simulation (MBS)

Nowadays, finite element method (FEM) simulations are state-of-the-art for crashworthiness evaluation. In contrast to FEM simulation, where the element number is often more than a million, a multibody system is reduced to a few bodies, which significantly reduces the computational effort. This advantage is specifically useful during the concept phase, where many different concepts need to be assessed. MBS exist of bodies, respecting the mass, connecting elements (joints), and constraints, representing the technical system's mechanical performance - in this case, with regard to vertical crashes.

4.2.1 Model build-up

The model build-up must represent significant geometric and physical characteristics and can be based on analytical preliminary considerations and calculations (4.1 Design of Energy Absorbing Systems). The simulation aims to investigate the four derived load cases (Table 1).

In this work the MBS software Siemens Madymo is used. In order to explain the model build-up, Figure 7 shows the masses, visualized by yellow ellipsoids. Connecting elements (joints + constraints) can be fixed, translational, or universal-translational and connect the individual masses to a kinematic chain. They are visualized via green symbols representing the constraint degree of freedom according to Figure 7th legend. The docking-unit (overhead mass) and the interior are connected fix and represent the vehicle's structure mass. The occupants are predefined dummy models. They contain sensors whose output signals include accelerations and forces and allow interpretation of biomechanical parameters. The representation of inmates is realized via FAA Hybrid III 50 % dummy, because this dummy enables evaluating spine and lumbar loads [36]. The lumbar load estimation via MADYMO dummies is validated [37]. Seat surfaces are used to simulate the dummies' concrete positioning and sitting posture.

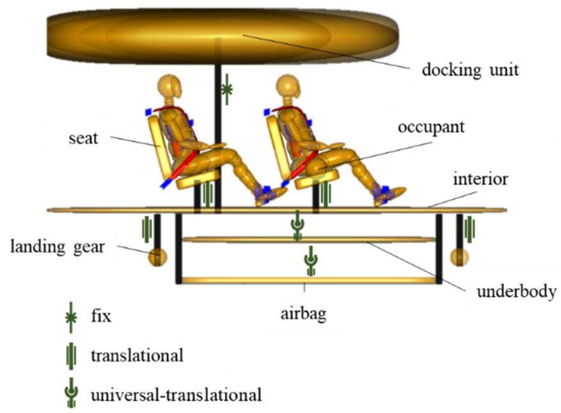

Figure 7: Multibody simulation model build-up visualization (Software: Siemens Madymo)

4.2.2 Simulation Findings

The following section describes the multibody simulation findings, which are based on the analytical pre-considerations (4.1 Design of Energy Absorbing Systems) supplemented with the mathematical optimization method (ARSM).

Figure 8 shows the acceleration course for the interior system and the pelvis of the Hybrid III 50% FAA dummy [36] for the crash load case READT (see). The maximum pelvis' acceleration is reached after 55 ms with a peak of 4.4 g, which is slightly over the target value of 4 g but is classified as uncritical for the duration of 10 ms. The landing gear was capable to prevent a contact between the vehicle's underbody and the ground with a force level of about 100 kN.

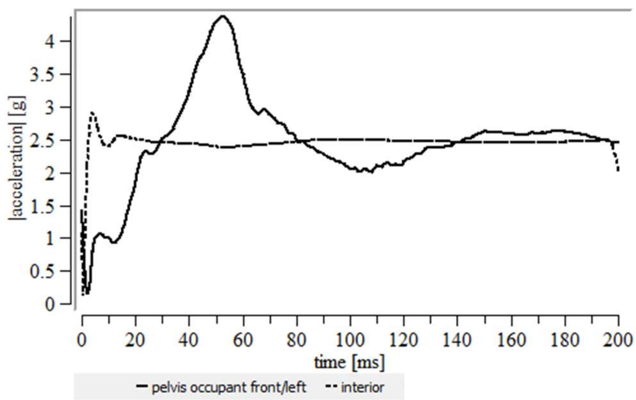

Figure 8. Acceleration course over time for load case READT

Analysis of the VC 1 load case, shows pelvis acceleration peaks of about 11 g and an average acceleration of 10 g over a time period of 100 ms (green area in Figure 9).

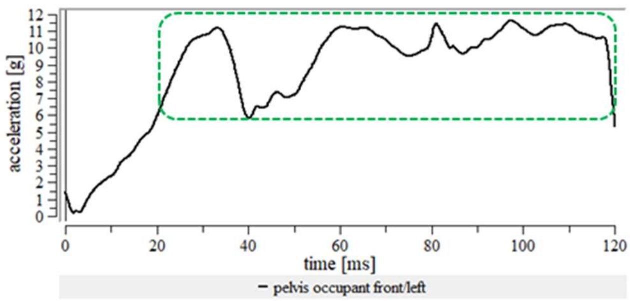

Figure 9. Vertical crash 1 – pelvis acceleration over time history

Simulation results for the crash load case VC 2, show peak accelerations of about 80 g at 30 ms and an average acceleration level of approximately 25 g for a period of 70 ms (yellow area in Figure 10)

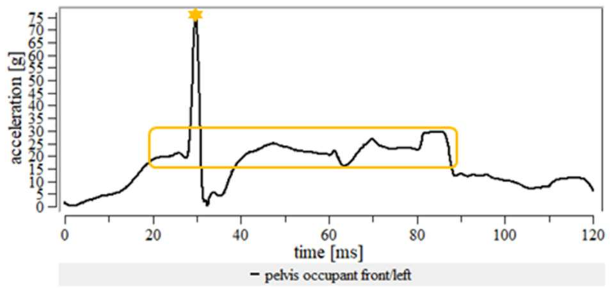

Figure 10. Vertical crash 2 – pelvis acceleration over time history

Evaluating the crash load case simulation results via the Eiband-diagram to identify occupants' injury probability, VC1 shows results in the area where occupants are expected to be uninjured (see Figure 11). Both VC2 results, the average accelerations over a time period of 70 ms (yellow box in Figure 10 and Figure 11) as well as the acceleration peak of 75 g at 30 ms (yellow star in Figure 10 and Figure 11), can be classified in the area of "moderate injury".

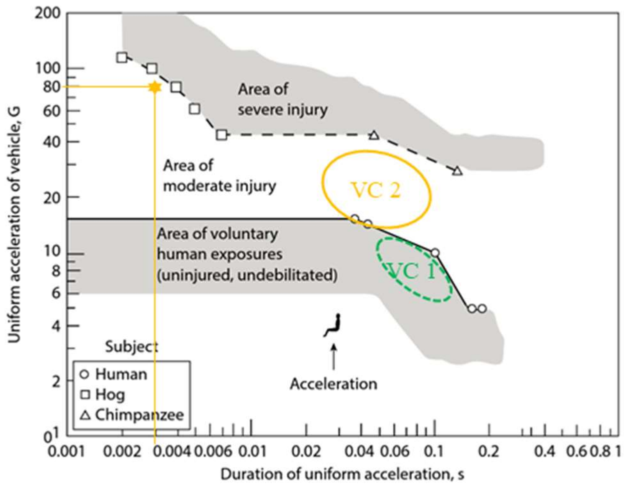

Figure 11. Injury probability evaluation for load case vertical crash 1 and 2 based on occupants' vertical accelerations over the time using the Eiband-diagram

While the maximum lumbar load criteria of 6674 N was achieved for *Vertical Crash 1* (3620 N), it is exceeded for *Vertical Crash 2* (8000 N).

5. Conclusion

In this work, the crashworthiness of eVTOL has been investigated. By analysing accident events, probabilities and severities, vertical impacts have been determined as the most important crash impact conditions. Four crash load cases and corresponding evaluation criteria have been defined, analysing existing helicopter and small airplane certification specifications, crash investigations and biomechanical load limits. A corresponding eVTOL crash concept with four energy absorbing systems has been developed for the vertical impact conditions using analytical and the mathematical optimization method ARSM. Multibody simulations show that even with a landing gear exceeding slightly the acceleration target of 4 g in the READT load case, while fulfilling the requirements of VC1, VC2 evaluation criteria (lumbar load & occupant acceleration) could not be achieved.

While the analytical approach is a quick method to find parameters for a basic crash concept and to get an idea about the physical magnitudes, it becomes quickly complex and inefficient considering the wide range of possible eVTOL crash configuration variations. Even though the energy-absorbing crash sub-systems (passive structure, landing gear, seat console, airbag) are referenced and can be validated via tests according to mechanical characteristics, the system's full-vehicle performance needs to be validated. However, this work is considered a good approach to better understanding eVTOL's crashworthiness, as long as no full-vehicle crash data is available.

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