Challenges in Vehicle Safety and Occupant Protection for Autonomous electric Vertical Take-off and Landing (eVTOL) Vehicles

Justin Littell

Structural Dynamics Branch

NASA Langley Research Center

ABSTRACT

The burgeoning electric Vertical Take-off and Landing (eVTOL) vehicle industry has generated a significant level of enthusiasm amongst aviation designers, manufacturers and researchers. This industry is determined to change the urban transportation paradigm from traditional ground-based vehicles (cars, taxis, buses) to air-based eVTOL vehicles which can be summoned, much like how conventional taxi services work currently. These new eVTOL vehicles are designed to be small and lightweight and operate autonomously without user intervention.

There are many unknowns as to how the industry will mature. The logistics of creating a completely new category of vehicle along with its own set of rules are complex, and there are many known - and unknown - barriers to overcome. Some (of many) known barriers include airspace management, ground logistics, physical space, and, the vehicle design itself. There are many eVTOL vehicle manufacturers and organizations working these problems presently.

This report will focus on one major barrier: the level of safety as it pertains to the framework of eVTOL vehicles. A high level of safety is necessary for the vehicles to gain acceptance as the public adapts to these autonomous ride-sharing services. An overview of current levels of transportation safety and some extrapolation into how eVTOL vehicles might compare is first presented. Next, a discussion categorizing the major differences between *Crash Prevention* and *Crash Mitigation* as it pertains to eVTOL vehicle safety is included with identification of current deficiencies. The report then expands into a framework for specific ideas that could use *Crash Mitigation* to improve vehicle safety through a crashworthy systems level approach with several designs highlighted.

Finally, a brief discussion into the regulatory approach and potential guidelines as they pertain to new eVTOL vehicles is presented. Accordingly, much of the supplemental data will be taken from sources pertaining to either General Aviation (GA) aircraft, rotorcraft, or transport category aircraft, due to the lack of overarching data from eVTOL vehicles. As of this writing, the European Aviation Safety Agency has released a draft version of a VTOL Special Condition, with a comment period closing in late 2018. It is assumed that eventual expected operations and anticipated future regulations for VTOL vehicles will consist of some combination of these (and other) sources.

Introduction

The emergence of the new Urban Air Mobility (UAM) markets will change the paradigm of urban-based travel from conventional methods like cars, busses and taxis to on-demand aerial-based travel services using new electric Vertical Take-off and Landing (eVTOL) vehicles. These vehicles, which are currently in development, are designed to carry generally between 2 and 10 passengers, fly short routes within urban environments, provide quick turnarounds for arrivals and departures, and operate autonomously. Many manufacturers (OEMs) are currently in the design and prototype phases of vehicle development and many of the vehicle designs use composite materials, distributed electric propulsion (DEP) and numerous rotor blades in various configurations. There are a significant set of hurdles that must be overcome before actual operations can begin and many eVTOL OEMs are working toward solutions.

The major area that will be discussed in this report relates to the safety of vehicle operations, and, more importantly, the features and systems that can be utilized in order to provide enhanced occupant protection in the event of a mishap.   There are many other features that will need to be addressed prior to eVTOL operation in the UAM markets such as autonomy considerations [1], noise [2], airspace factors, communication factors and weather. This report, however, will focus on the safety of the vehicle itself and how it protects the occupant from a mishap or crash. A discussion regarding systems which can be included on the vehicle itself along with ways of defining regulations to ensure a high level of safety will both be covered.

Vehicle Regulations and Levels of Safety

In the United States, under current air carrier operations for paid flights (flights for hire), there are two operational models. The first is 14 CFR § 121, which covers all of the major airlines which fly regularly scheduled routes, and the second is 14 CFR § 135, which covers on-demand flights like aerial sightseeing, charter operations and air taxi. Generally, commercial air travel on the major airlines (which fall under 14 CFR § 121) is safe [3], mainly due to the regulations put in place by the Federal Aviation Administration (FAA) over the course of its existence. The number of accidents that occurred on 121 aircraft is 0.16 per 100,000 flight hours. In contrast, the number of accidents that occurred on 14 CFR § 135 aircraft is 0.42 per 100,000 flight hours. While rare, accidents do occur, and when they do, it is the FAA’s task to define the problem and mitigation strategy. The solution developed is usually communicated to the industry using Advisory Circulars or other guidance that then becomes updated policy.

Uber has taken an interest in defining what the level of safety of eVTOL vehicles operating in UAM environments should be. In their white paper [4], Uber suggests setting a safety goal of twice that of driving a car, based on the fatality rate per passenger mile. This level of safety, Uber suggests, corresponds to a level that is one quarter of 14 CFR § 135 levels, or as Uber suggests, twice as safe as driving a car [4].

For eVTOL vehicles, the vehicle designs will resemble smaller aircraft similar to General Aviation (GA) (14 CFR § 23) or utility helicopters (14 CFR § 29), and fly using an operational model similar to on-demand (14 CFR § 135) operations. Accident data from 2014 [5] for GA aircraft shows that the three factors that cause the highest number of fatal accidents are the following: Loss of Control, System (Power) Malfunction and Unintended Flight into instrument meteorological conditions (IMC).   The first two factors relate to the vehicle and its operation while the third refers to unintentionally flying into poor weather conditions. For 14 CFR § 135 non-scheduled accidents for helicopters, which the author thinks are the closest analogy to an eVTOL operational model, the two highest causes of accidents are Loss of Control-Inflight and System (Powerplant) Malfunction. Low Altitude Operations and Collision are listed as two additional causes for accidents. The data is provided to suggest that for both GA and 14 CFR § 135 non-scheduled helicopter operations, the major factors that must be addressed to ensure safe flight are maintaining control of the aircraft during all phases of flight and to provide capabilities against powerplant failure. Fortunately, there are many crash prevention systems under development that will address these events.

For guidance regarding the inclusion of systems to achieve high levels of safety in aircraft, the automotive industry can be used as a case study for regulations. The automotive industry utilizes the regulations defined in the Federal Motor Vehicle Safety Standard 208 [6] as the basis for crashworthiness and occupant protection. This document originally stipulated the inclusion of seat belts for all automobiles manufactured after January 1, 1968, led to the use of vehicle crash testing by the mid-1970’s, to the inclusion of airbags in 1998 and other crashworthy features that become standard on all automobiles manufactured today [7].

The additional requirements for safety in the document were a direct result of vehicle testing and also accident data collected over the years. This document is mentioned because it is the author's opinion that the intent of continual improvement in crashworthiness systems through testing and data analysis should be included in some form as new eVTOL vehicles and regulations are developed.

While not regulatory requirements, there are additional ways that automotive safety can be quantified. Both the National Highway Traffic Safety Administration (NHTSA) [8] and the Insurance Institute for Highway Safety (IIHS) [9] conduct their own crash tests on full-scale vehicles to evaluate crashworthiness characteristics. Ratings usually occur on a scale from one to five with five being the highest. In many cases, automotive OEMs will include a high crash rating in literature of their products. Once eVTOL vehicles begin operations, if analogous types of tests are conducted, then eVTOL OEMs can claim high levels of safety to assist in overall acceptance by the general public and potential end users/customers.

A general summary of eVTOL operations can be stated as follows: the vehicle designs will most resemble GA aircraft (14 CFR § 23), small helicopters (14 CFR § 29) or a combination thereof, fly using an operational model similar to on-demand (14 CFR § 135) operations, carry numbers of passengers akin to major air carriers (14 CFR § 121), thereby replacing routes normally travelled in automobiles (FMVSS-208). Discussion regarding ways to characterize the new regulations will be discussed in the *Regulatory Considerations for Certification* section of this report. However, a discussion on *Crash Safety* is first presented to familiarize the reader with current crash safety systems along with proposed technology necessary in order to provide crash mitigation.

Crash Safety

NASA Case Study

A series of vertical drop tests were conducted in a vertical drop tower located at NASA Langley Research Center (LaRC) in 2018 [10]. In this test series, vertical impacts from a height of 14 ft., corresponding to an impact velocity of approximately 29 ft./s, were conducted on Anthropomorphic Test Devices (ATDs, a.k.a. crash test dummies) undergoing deceleration pulses used for rotorcraft [11] or transport category aircraft [12] seated in certified transport category aircraft [12] seats. The tests utilized ATDs with a size range between 5th and 95th percentile. In these results, the 95th percentile ATD exceeded the lumbar load injury limit specified by the FAA of 1,500 lbs. in almost every test pulse tested. (It should be noted that the l,500 lb. limit officially applies to a 50th percentile ATD and therefore is likely low for a 95th size ATD. However, there are no civilian guidelines for 95th sized ATDs for lumbar load, so it is presented only for reference.) Additional results show that the rotorcraft pulse [12] resulted in lumbar loads exceeding the injury limit. While these results are not directly applicable to eVTOL configuration due to the unknown seat designs, impact conditions and occupant type, they demonstrate that even at low altitude impacts, injury limits can be exceeded. Figure 1 shows the test setup, with the ATDs seated at the 14-ft. drop height.

Figure 1 - ATD drop tests conducted in 2018. ATDs at 14-ft drop height prior to impact

It is conceivable that the height shown in Figure 1 could represent some type of off nominal event and could cause an eVTOL vehicle to miss its landing spot by this height due to a variety of unknown factors. If this scenario were to occur, crash mitigation systems are needed.

Crash Prevention vs Crash Mitigation – Main Differences between Automobiles and eVTOL vehicles

There are two main ways to ensure occupant protection in a vehicle design: crash prevention and crash mitigation. Crash prevention involves designing systems that prevent an accident from occurring in the first place, while crash mitigation involves designing systems that provide protection from a crash occurrence.

In automotive design, crash mitigation technologies (seat belts, airbags, crumple zones) have long been engineered and implemented over the past 100 years, with regulations dictating their utilization, as previously discussed. It is only more recently that the automotive OEMs have investigated crash prevention technologies. Crash prevention systems on automobiles such as lane assist, adaptive cruise control and automatic braking systems [13] are currently under development and are designed to prevent the automobile from entering an unsafe condition. Some of these systems are currently in use in conventional automobiles now, and it is presumed that they will also be used in conjunction with additional autonomy systems for autonomous automobiles in the future.

For eVTOL vehicle design, the reverse is occurring. Vehicle OEMs are focusing on crash prevention when addressing the concerns for autonomous operation. Onboard systems such as RADAR, GPS, and other sensors and cameras all provide collision avoidance capabilities; however, not a lot of literature/data is publicly available that discusses crash mitigation technologies such as crushable structures, energy absorbing seats and other technologies.

One notable item to illustrate is that the current business model for autonomous automobiles relies on retrofitting of *existing vehicle*s with self-driving systems, making sensor design, placement and functionality constrained to the existing vehicle design. (There are startup companies beginning to develop autonomous vehicles from the ground up, but those are not in operation yet.) For eVTOL vehicles, since the vehicle designs are essentially "starting from scratch", crash prevention and mitigation technology can be built in at the beginning of the design process. The opportunity exists to both optimize the vehicle structure for automation systems, but also allow for crashworthy mitigation systems to be developed prior to the first crash event taking place. The next section will focus on some of these types of prevention systems that are being used on current prototype and experimental aircraft, along with mitigation systems that have been used on aircraft in the past and can be utilized for eVTOL crash mitigation.

Safety Systems Capabilities

eVTOL Vehicle Crash Prevention

Crash prevention systems for eVTOL vehicles involves many of the same systems already being used in autonomous automobiles. These items include cameras, radar, LIDAR, GPS, infrared scanners, and a host of others. Further crash prevention is necessary in the powerplant and rotor systems to allow the eVTOL vehicles to remain in flight if a powerplant or rotor failure occurs. These additional systems include redundancy in the motors and batteries, typically called Distributed Electric Propulsion (DEP), and are designed in such a way that if a single component should fail, the others would be able to function in order to safely guide the aircraft to a landing.

There is also a large body of research regarding vehicle separation, vehicle communication and airspace integration, which can be generally grouped into "airspace management", which is also a big part of crash prevention. However, since this report primarily focuses on the structure of the vehicles themselves, these topics will not be discussed in detail. However, there are many other documents available, such as ref. [14] that detail the challenges required regarding these airspace issues.

NASA's X-57 "Maxwell" concept vehicle [15] is a part of NASA's X-plane research and is a flight demonstrator for DEP technology. A Technam P2006T aircraft [16] will be modified by removing the wing, engines, and associated equipment, and be replacing with a new, smaller distributed propulsion wing and a high-voltage electrical system that includes over 800 lb. of lithium-ion batteries. The X-57's wing will include two larger electric motors and propellers at the wingtips for primary propulsion, and 12 "high-lift" motors with foldable propellers that will only be operated at low speeds to augment takeoff and landing flight characteristics. The fuselage, tail, and other features will remain the same as the original P2006T.

Systems Level Crash Mitigation

Crash mitigation systems information present onboard eVTOL aircraft is not as well documented in publically available literature. Historically, crash mitigation systems are designed into a "systems level" approach (sometimes referred to as "systems level crashworthiness"), where multiple onboard systems are available to help mitigate the crash loads. The systems level approach has been used extensively in civilian

[17] and military [18] aircraft designs, which can be used to assist eVTOL vehicle design. Figure 2 shows a graphical representation for the systems level approach of a crashworthy aircraft.

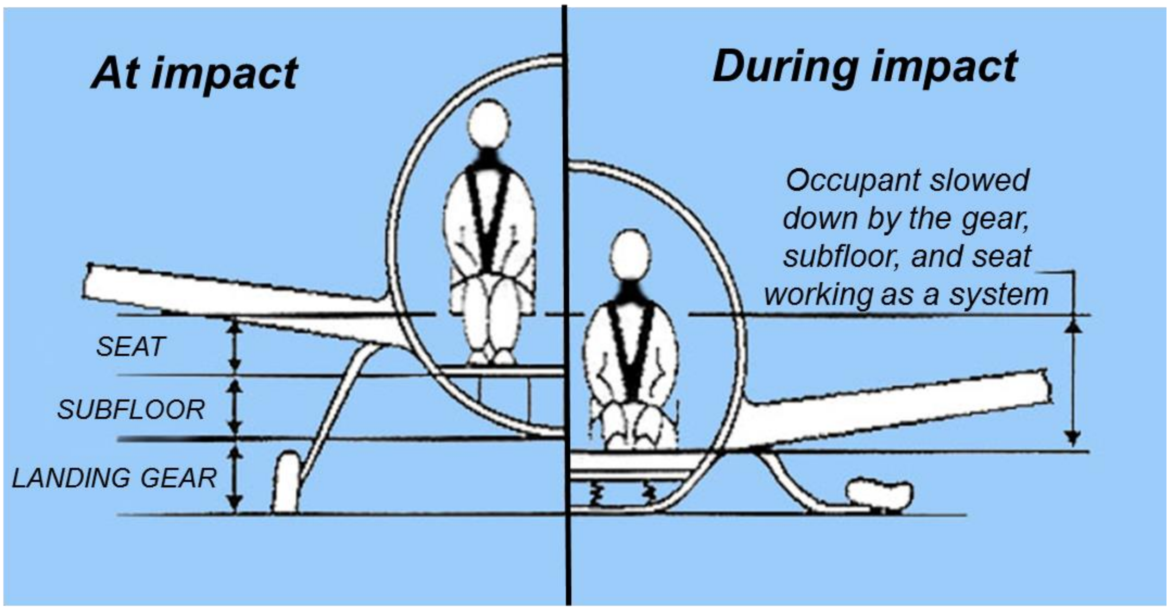

Figure 2 - Crashworthiness systems level approach

Figure 2 shows the crashworthiness systems level approach at impact. The landing gear is the first component that is capable of absorbing some of the crash energy through its deformation when making ground contact. The subfloor is the next component capable of crush to absorb some of the impact energy and finally the seat is able to deform. It is anticipated that all three features working together can provide sufficient energy attenuation such that when the impact reaches the occupant, it is at sub-injurious levels. Crashworthy vehicle designs have shown show that a systems level approach to *crash mitigation* will attenuate the energy at impact [19]. A sample of these systems are discussed in the next section.

eVTOL Potential Vehicle Crash Mitigation Systems

While not specifically illustrated in Figure 2, external protection systems such as airbags or other components (if installed) are the first means of attenuating impact energy during crash. External airbags function much like how internal airbags are used for automotive applications. They remain stowed until an anomalous condition is present. They would be located in the bottom/belly of the aircraft, deploy and function as cushions by venting their internal gas in a controlled manner upon impact. One instance in which they have been tested for use is the F-111 cockpit airbag test program [20]. In the F-111, the cockpit was designed to separate from the rest of the aircraft in the event of an emergency and act as an "escape module" for the crew. The Air Force determined that even with the parachute on the escape module, the impact with the ground resulted in a high number of injuries and fatalities. An external airbag system was designed and retrofitted beneath the cockpit area, and a series of 60 tests were conducted at NASA LaRC to determine the attenuation of occupant loads due to the addition of the airbags at various impact attitudes and velocities. The results [21] state, that the data acquired from the NASA LaRC tests led to a redesign of the blow-out plugs and the redesigned airbags were included in the F-111 fleet prior to retirement. Figure 3 shows an F-111 test conducted at NASA LaRC.

Figure 3 – F-111 Test article. *Reprinted from [20]*

A more recent test conducted by Boeing demonstrated technology called the Active Crash Protection System (ACPS), which was a series of sensors along with an airbag system designed to improve the crashworthiness of an aircraft [21]. A full-scale drop test of the system was conducted to evaluate the ACPS performance and to determine the performance of four attached airbags to attenuate combined vertical and horizontal impact velocities. The results showed peak vertical acceleration maximums of less than 20 g; however, only one of the burst disks opened upon impact, leading to higher-than-predicted loads.

There are many reasons why impact energy attenuation through the use of airbags proves difficult in real world scenarios, which is why they are not seen on current fleets. As demonstrated with the Boeing test, while it was only a demonstration of concept, complications in airbag systems, both through the gas generation system but also the anomaly with the burst discs, are factors that, without additional development testing, preclude them from being used on aircraft fleets today. And while the airbag concept is one alternative solution, validation of any technology must be first demonstrated, as shown by the necessity of 60+ tests which needed to be conducted on the F-111 cockpit.

One potential alternative to an airbag system is a crushable concept called the Deployable Energy Absorber (DEA) which was developed by Kellas [23] at NASA LaRC. This design utilized a hinged hexagonal honeycomb system fabricated from a Kevlar ® composite material. The DEA was designed to crush thought a controlled folding pattern in the cell walls. After a series of subscale tests to prove the concept, this DEA system was successfully utilized on a full-scale crash test of a MD-500 helicopter [24]. The DEA was configured into the deployed condition for test, and was able to attenuate the lumbar loads into the ATDs by up to 67% from an impact of 40 ft/s. forward and 26 ft/s. vertical velocity when compared to an identical MD-500 test conducted without the DEA underneath the body of the helicopter [25]. Figure 4 shows the crushed DEA post-test.

Figure 4 - MD-500 with DEA post-test

The DEA components are shown as the yellow structures below the aircraft, approximately in-line with the vertical supports of the landing gear system. Two DEA components were used in order to support the front and rear rows of occupants. The DEA components crush and folded in a nominal manner, and reduced the loads into the occupants upon impact. The lumbar load data, as measured in the pilot ATD, is shown in Figure 5.

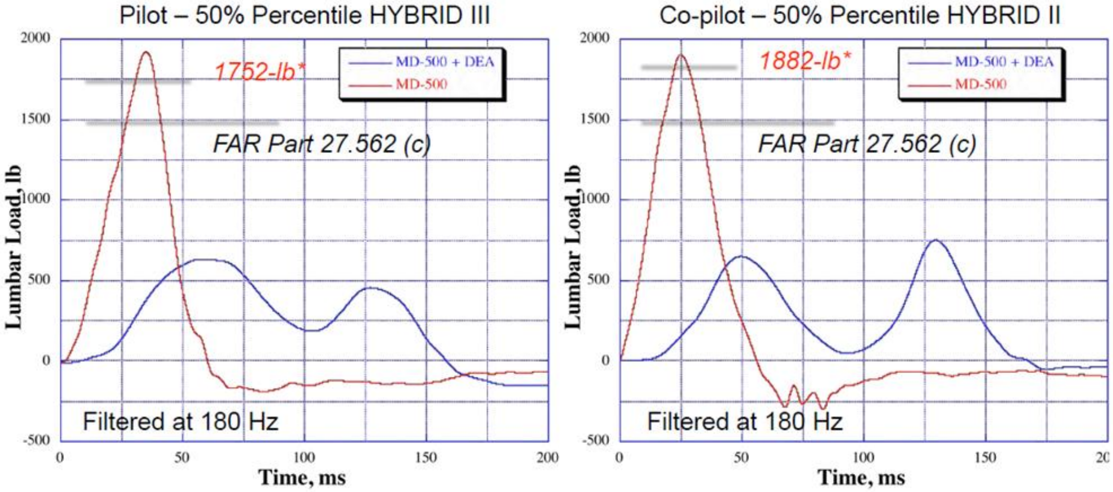

Figure 5 - Lumbar Load values for the Pilot and Co-Pilot. *Reprinted from [25]*

In the systems level approach, the landing gear is the next available system capable of attenuating any of the impact energy. The landing gear can bend or plastically deform (similar to what is shown in Figure 2) or can contain components specifically designed to deform or crush for energy attenuation. For larger aircraft, one common design for a landing gear is the oleo-strut system, which is a two chamber oil-air system designed to cushion the impact under normal landing circumstances. In a crash event, the landing gear struts are designed for crashworthiness, and can attenuate impact velocities up to 42 ft./s like those systems used in the UH-60 helicopter [26].

However, the weight penalty imposed by using the oleo strut design will likely preclude them from being used on an eVTOL vehicle that will likely weigh less than 2,000 lb. In this instance, other designs such as composites or crushable lightweight material must be used to attenuate the impact energy. Since most eVTOL OEMs state they will be using carbon composite materials instead of traditional metallic materials to save on weight, investigations into lightweight crushable materials are needed. The major challenge in using carbon composite materials is that the carbon fibers do not contain the ductility of traditional metallic materials, and, as such, will not bend upon impact. There have been many studies on carbon crushable structures, and the results show brittle failure characteristics with the carbon materials pulverizing, splaying or peeling when being subjected to crush loads [27-28]. This method of failure typically occurs at higher specific energy, and if an eVTOL vehicle should use the carbon material as an energy absorbing mechanism, the design will need to be optimized to ensure transmitted loads are of a survivable level.

A recent study conducted by NASA LaRC in 2018 examined a series of hybrid material systems for their use in crushable energy absorbing mechanisms [29]. In this study, hybrid woven composite specimens consisting of carbon in the warp direction and Kevlar® in the fill direction were fabricated into tubular shapes for investigation into their energy absorbing capabilities. These hybrid systems were then compared to tubular specimens fabricated from carbon composite only. Figure 6 shows images of tubes fabricated from both the traditional carbon and the hybrid material systems.

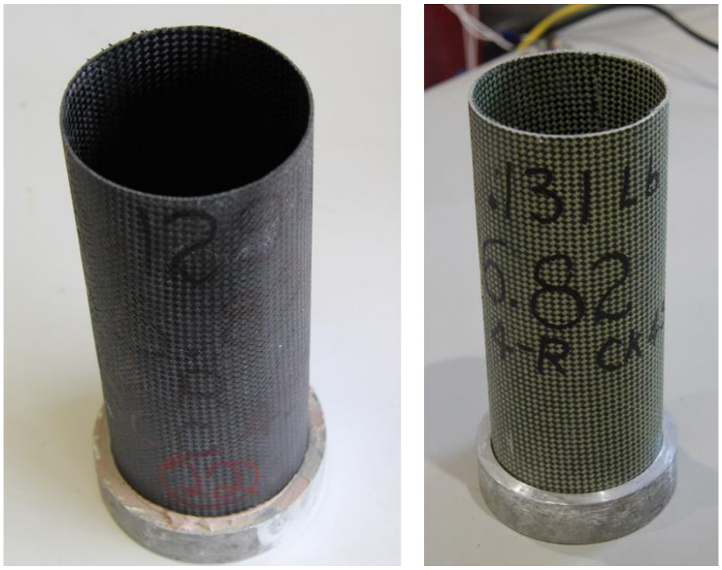

Figure 6 - Composite tube specimens. Traditional carbon (left) and hybrid carbon/aramid (right) weaves

While the design and results are preliminary, the results showed that these hybrid systems can produce deceleration pulses of less than 20 g through a controlled folding pattern made possible by the ductility of the Kevlar ® fibers. This characteristic folding mechanism is shown in Figure 7, right.

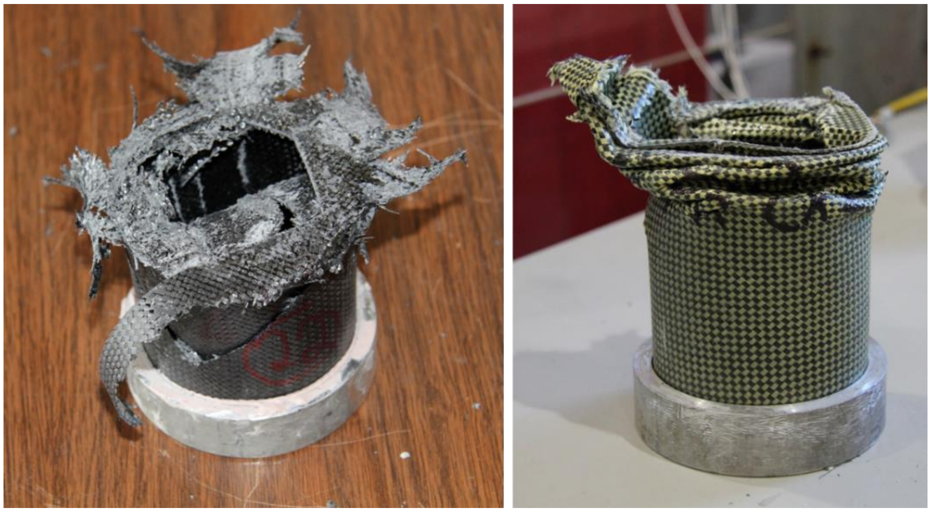

Figure 7 - Crush tube post-test deformation

The folds shown in the hybrid carbon/Kevlar specimen in Figure 7, right, allow for a controlled crushing of the tube itself. This response is in contrast to the full carbon specimen shown on the left. In the full carbon specimen, which was manufactured with an equivalent layup, geometry and shape to the hybrid system shows splaying and a buckle in the lower portion of the specimen, indicating unstable crush. While these results were originally intended as a means of screening various layups and geometries, it is clear the in this specific configuration the hybrid system is capable of exhibiting crush characteristics that could benefit from the controlled crushing. However, both systems could and should be optimized for use in actual vehicle design, should they be included.

The subfloor area is the next item that can be utilized to benefit the crashworthiness of the aircraft. Items such as the keel beams and frames can all be optimized to crush and fold, or if these traditional structures do not exist on eVTOL aircraft designs, items such as honeycombs or foam can be included with minimal weight penalty. There are examples of subfloor geometry [30] and subfloor materials [31-32] being optimized to withstand crush loads. Figure 8 shows an example energy absorbing (EA) keel beam retrofit for use in GA aircraft.

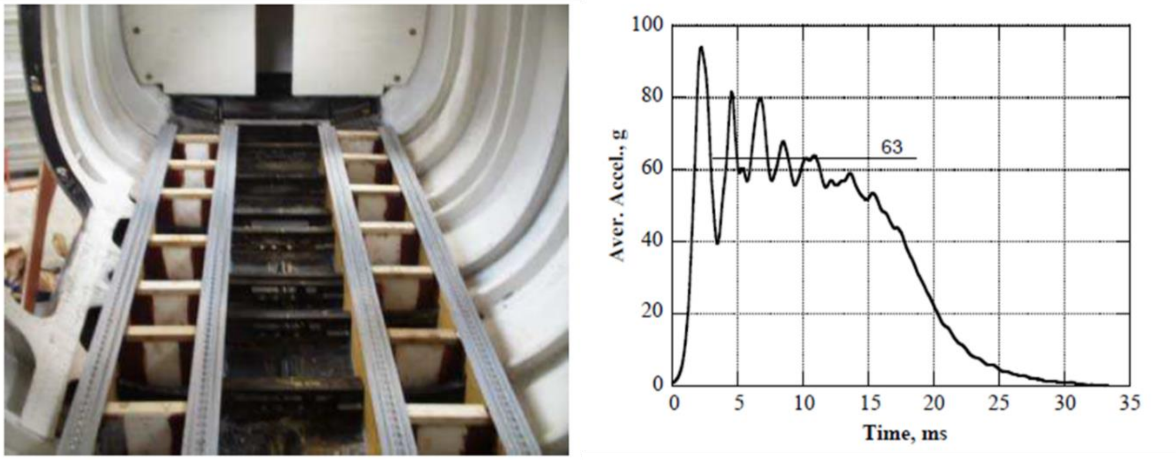

Figure 8 - Energy Absorbing Keel Beam. Installed in mock-up aircraft (left) and a component level crush test acceleration response (right). *Reprinted from [31]*

The keel beam component level test showed an average deceleration response of 63 g, which is too high of a limit for eVTOL vehicles. However, the design concept is not without merit. The crush response, with some further development, can be tailored to suit any type of loading level needed, and thus the concept can be adjusted for the eVTOL environment.

A properly designed seat and restraint system is the final component of a systems level crashworthiness concept. The seat can serve a dual role. The first is to provide additional attenuation from the impact event. The second is to act in conjunction with the restraint system to keep the occupant restrained during impact to mitigate the potential for secondary object strike (i.e. striking an internal aircraft component such as the yoke or console). Research has shown that a properly designed seat, along with the correct restraint system can significantly improve occupant protection during a crash [33].

A major safety component that many OEMs highlight is a Ballistic Recovery System (BRS), which is a parachute designed to be deployed in the event of an off-nominal condition. BRS systems were originally developed for Cirrus aircraft [34], and BRS systems have since been installed on numerous makes and models of aircraft. BRS Aerospace, which is the commercial supplier of the BRS systems, currently has a placeholder for VTOL aircraft on their website [35], however, no aircraft are listed as of this writing. However, in a press release [36], BRS aerospace states that they are developing and testing protocols to evaluate the safety and performance of aircraft parachute recover systems in GA and VTOL aircraft.

It is the author’s opinion that a parachute or BRS system should be a required piece of equipment for all VTOL vehicles. However, because flight characteristics will be different between a VTOL vehicle and a conventional GA or Light Sport Aircraft (LSA), the optimization of the BRS system is a necessity. Cirrus, in their CAPS literature, states a successful deployment has occurred from as low as 400 ft. in altitude in straight and level flight. The literature does not give a lower deployment limit, which should be a major consideration for use in frequently low-flying eVTOL vehicles, and it should also be noted that eVTOL vehicles may not be demonstrating straight and level flight during all phases of their mission.

The lower deployment limit will be a fundamental difference between how a BRS system performs currently and how it must perform for VTOL vehicles. While actual flight data does not exist for VTOL vehicles currently, looking at the mission profile supplied by Uber [37], “ground taxi”, “hover climb”, “transition climb” and “terminal departure” all occur at or below 300 ft. above-ground-level (AGL), with only “Accel+Climb”, “Cruise” and “Decel+Descend” occurring higher than 300 ft. AGL. While these lower altitude segments may only occur for a small percentage of the total time for each mission, these segments account for the largest percentage of mission tasks. With the additional expectation of many of these missions will occur per day, the number of segments that occur at or below 300 ft. AGL will be quite large for any one vehicle per day.

eVTOL Systems Level Crash Mitigation Analyses

A preliminary study [38] was conducted by running computer simulation analyses on the NASA VTOL concept vehicle #1 [39] in order to examine the effect of the inclusion of crashworthy structure onto the onboard (simulated) occupant, represented by an ATD. In this study, the generic concept vehicle was subjected to an impact of 30 ft./s, with an occupant, simulated by a Hybrid III ATD seated in a single rigid seat. The study was conducted by sequentially adding layers of crashworthy systems and examining the effect on the occupant lumbar load. Items that were added include: subfloor structure, seat foam, seat energy absorbing strut, energy absorbing landing gear, and finally, energy absorbing landing gear struts. Figure 9 shows illustrations of the NASA VTOL concept vehicle, both in the baseline configuration and with the fully added crashworthy components.

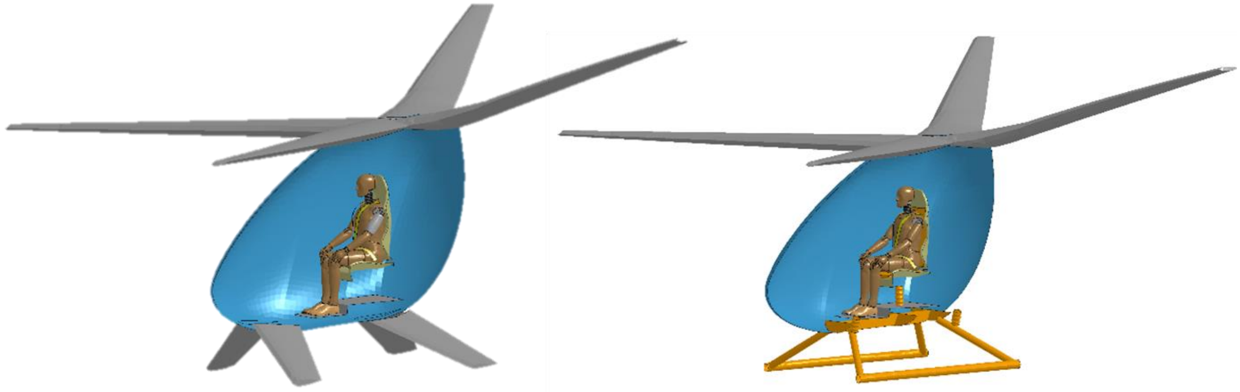

Figure 9 - NASA VTOL concept vehicle model. Baseline configuration (left) and configuration including crashworthy components (right)

Each component was added in addition all other previous components in order to examine each individual's improvement in the overall occupant protection. Using baseline crashworthy component designs not optimized to achieve its highest level of specific energy absorption, the final results showed that a vehicle with all of the included crashworthy features reduced the lumbar load on the occupant by 87%, along with reducing the overall vehicle weight by 169 lb. While this study was not intended to qualify the NASA concept vehicle's specific crashworthy characteristics, and the simulation results have not been validated by full-scale testing, the trends show clear improvement in occupant protection when crashworthy systems are included. Figure 10 shows the lumbar load comparison between the baseline and included crashworthy concepts, noting that a negative load value indicates compression at the lumbar spine location.

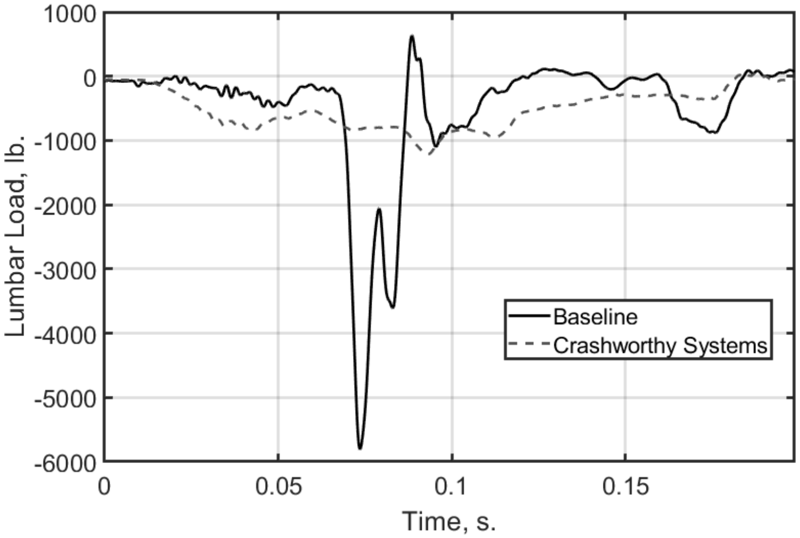

Figure 10 - Lumbar load comparison

Some companies are recognizing the systems level approach and have noted the use of various crushable systems and energy absorbing mechanisms in their designs. Transcend Air, in a press release, states the use of the BRS in conjunction with "…frangible aircraft structure, safely deforming seat supports and airbags." [40]. However, specific details of the final design are not identified at the time of writing, because the aircraft is only in the scaled prototype phase of design.

An effective systems level crashworthiness approach can utilize all of the previously mentioned and many other concepts and components. Caution must be used, however, when combining separate components to ensure that each component functions effectively when combined with the others. For example, crushable floor structure designed to limit floor loads to 12 g used with a 16 g stroking seat would negate the effectiveness of the seat, and thus not adequately provide the maximum of occupant protection. Systems must be optimized in the vehicle design stage in order to provide the most occupant protection. The author also recommends that these systems must be tested as a system, either through a full-scale test or analysis program to ensure their functionality and robustness of design, similar to the analyses completed for the NASA concept vehicle.

With the inclusion of a systems level crash mitigation approach, eVTOL vehicles are in a position to be able to provide a level of protection necessary to satisfy the level of safety necessary for vehicle certification. However, a component necessary to achieve certification is the rules and regulations themselves.

Regulatory Considerations for Certification

The regulations to which vehicles must adhere do not currently exist, and a path to certification, while there has been discussion, is ultimately unknown at the time of writing. The various regulations that have been suggested for eVTOL vehicles include: 14 CFR § 23 - which is used for GA airplanes, 14 CFR § 29 - which is used for utility helicopters, and 14 CFR § 21.17(b) - which include all "other nonconventional aircraft". There is current discussion and debate in the community regarding which regulation(s) (or a combination thereof) should eventually be used.

Regulations must not be overly prohibitive such that OEMs cannot enter the market in a reasonable manner. This was the intent in going into Part 23 Amendment 64 (sometimes called the "Part 23 rewrite"), specifically defining level of performance that can be achieved through the aircraft design instead of a prescriptive requirement. It is up to the applicant to define the compliance in which the performance is achieved, which could be considered one way for Part 23 (or new Part) certification. The rewrite is intended to speed up the certification process without imposing any undue cost burden on each applicant/OEM, which would expedite the certification process for eVTOL vehicles. Additionally, the rewrite allows for outside organizations to develop Means of Compliance (MoC) standards for applicants to use for certification. One of these organizations is ASTM International, which develops standards for a wide variety of subjects. The committee on General Aviation (F44) is scoped to develop and maintain "standards and guidance materials intended to be acceptable means of compliance (MoC) for general aviation aircraft rules and regulations around the world."[41]. The draft document ASTM F3083 [42] is the proposed means of compliance document. Note that this is only one example means of compliance.

A second way to demonstrate MoC could be a rating system which gives points for the inclusion of crashworthy structures built into each vehicle. A similar rating has been previously proposed in a document entitled "Full Spectrum Crashworthiness Criteria for Rotorcraft" [42], which is intended to be used in new designs of conventional rotorcraft. The criteria defines a "Crashworthiness Index (CI)", which is a "quantitative measure of the rotorcraft's crashworthiness across multiple crash environments and conditions…" The CI provides a quantitative score to a particular aircraft design based on various contributing factors including the aircraft's mission profile, design, equipage and many others. Full details on how the CI index is computed can be found in [42].

However, in the first of its kind, in October 2018, the European Aviation Safety Agency (EASA) issued a Special Condition (SC) for "Small category VTOL aircraft. [43]." This SC is for small (5 or less passengers) aircraft with a total vehicle mass of 2,000 kg or less, which would not encompass the entire fleet of proposed design vehicles at present. However, at a minimum it does attempt to codify some of the overarching rules that the vehicles must adhere, and allows applicants (OEMs) to comply using acceptable means of compliance, which include acceptable consensus standards, similar to how new GA vehicles will be certified under amendment 64 of Part 23. It is unclear, however, due to the constraints in the text as to the applicability of how many eVTOL vehicle designs this would encompass.

Conclusion

This report discusses some (of many) issues that exist for the certification and public acceptance of new eVTOL vehicles. Examples of levels of safety are first presented for existing types of aircraft using data from various types of current vehicle certification, and then a discussion of what proposed levels of safety for eVTOL vehicles might be.

Many examples of ways to achieve these levels of safety are presented of systems and components that can be used in harmony to achieve a systems level crashworthiness concept. Many of the major eVTOL vehicle OEMs are suggesting a BRS system as the path of satisfying the crash mitigation; however, the unknowns regarding its performance for the UAM mission requirements and vehicle designs themselves leaves serious unknowns into its performance. At a minimum, the performance of a BRS must be studied in order to optimize its effectiveness under a variety of (still unknown) eVTOL vehicle crash conditions. Many additional crash mitigation concepts are presented as ways of attenuating impact loads, which included airbags, external energy absorbing systems, underfloor systems and seat. These components, working as a system, could have the capability of greatly reducing the loads into the occupants should a crash occur. However, these systems must be developed and tested as a system to ensure their effectiveness.

A sample crashworthy systems level analysis case is shown, which includes a reduction of occupant load of 87% on a generic NASA concept vehicle. This systems-level crashworthiness approach uses crushable structure for the landing gears and subfloor, and these types of systems and material could be used and built into any number of prototype of conceptual vehicles now.

The safety requirements which will eventually be codified into a rule by the FAA are additional items which will need to be defined. At the time of writing there is no consensus into the certification process, however, a discussion is presented regarding both a performance based criteria and a points system. Finally, a brief discussion is presented on the new EASA SC that was developed in late 2018 and how it pertains to eVTOL vehicle designs.

There is great enthusiasm and interest in this developing industry. With the proper steps taken to address the safety requirements of the vehicles through a systems level crashworthiness approach in conjunction with the appropriate regulation, the UAM industry has the capability of transforming the entire paradigm of urban transportation. The industry, while in its infancy, is changing rapidly, and changes/updates in vehicle design and regulation writing will have likely occurred since the time of this writing. It is hoped that the market realizes some of the crash mitigation concepts presented, along with many others not presented, and develops them into vehicle designs to ensure the safety is achieved at the highest level possible.

References

1. Littell, J.D. “Challenges for Vehicle and Occupant Safety in Autonomous Electric Vertical Take-off and Landing (eVTOL) Vehicle Crashworthiness.” Proceedings from the Vertical Flight Society’s 8th Biennial Autonomous VTOL Technical Meeting. January 29-31, 2019. Mesa, AZ.
2. Gorton, S.A. “NASA Revolution Vertical Lift Technology Project Research.” Aircraft Noise and Emission Symposium. February 27, 2018. Long Beach, CA.
3. Shepardson, D. “2017 safest year on record for commercial passenger air travel: groups.” https://www.reuters.com/article/us-aviation-safety/2017-safest-year-on-record-for-commercial-passenger-air-travel-groups-idUSKBN1EQ17L. Accessed April 23, 2019.
4. Uber Elevate. “Fast-Forwarding to a Future of On-Demand Urban Air Transportation.” October, 27, 2016. https://www.uber.com/elevate.pdf. Accessed April 23, 2019.
5. NTSB. 2014 NTSB US Civil Aviation Accident Statistics. https://www.ntsb.gov/investigations/data/Pages/AviationDataStats2014.aspx. Accessed May 3, 2019.
6. Department of Transportation. “Standard No. 208; Occupant Crash Protection.” 49 CFR § 571.208. Amended October 1, 2011.
7. Kratze, S. R. “Regulator History of Automatic Crash Protection in FMVSS 208.” SAE Journal of Passenger Cars: Part 1. Vol 104 Section 6. Pp 1497-1506. 1995.
8. NHTSA. Ratings. https://www.nhtsa.gov/ratings. Accessed April 23, 2019.
9. IIHS. Vehicle Safety Ratings. https://www.iihs.org/iish/ratings. Accessed April 23, 2019.
10. Littell. J.D. and Annett, M.S. “The Evaluation of Anthropomorphic Test Device Response Under Vertical Loading.” AHS International 74th Annual Forum & Technology Display. May 14-18, 2018 Phoenix AZ.
11. Federal Aviation Administration. “Emergency Landing Dynamic Conditions.” 14 CFR § 27.562. Amended November 13, 1989.
12. Federal Aviation Administration. “Emergency Landing Dynamic Conditions.’ 14 CFR § 25.562. Amended May 17, 1988.
13. National Highway Traffic Safety Administration. “Driver Assistance Technologies.” https://www.nhtsa.gov/equipment/safety-technologies. Accessed May 3, 2019.
14. Thipphavong, D. P. “Urban Air Mobility Airspace Integration Concepts and Considerations.” AIAA Aviation Forum. Atlanta, GA. June 25-29, 2018.
15. NASA. NASA Armstrong Fact Sheet: NASA X-57 Maxwell. https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-109.html. Accessed May 3, 2019.
16. Costrurzioni Aeronautiche Technam S.R.L., “ P2006T - Aircraft Flight Manual,” Doc. No. 2006/044, 4th Ed – Rev. 0. Italy. 2015.
17. Hurley, T.L and Vandenburg, J.M. “Small Airplane Crashworthiness Design Guide.” AGATE-WP3.4-034043-036. April 12, 2002.
18. Simula Inc. “Aircraft Crash Survival Design Guide Vols. 1-5.” USAAVSCOM TR 89-D-22A. December 1989.
19. Terry, J.E. “Design and Test of an Improved Crashworthiness Small Composite Airframe.” NASA CR-2002-211774. 2002.
20. Jackson, K. E. et al. “A Summary of DOD-Sponsored Research Performed at NASA Langley’s Impact Dynamics Research Facility.” Journal of the American Helicopter Society, Vol 51. Iss 1. January 2006.
21. Chambers, J. R. “Partners in Freedom: Contributions of the Langley Research Center to U.S. Military Aircraft of the 1990’s.” NASA SP-2000-4519, 2000.

22. Bolukbasi, A. et al. "Rotorcraft Active Crash Protection Systems." Proceedings from the 67th American Helicopter Society Annual Forum and Technology Display. Virginia Beach, VA. May 3-5, 2011.
23. Kellas, S. "Deployable Rigid System for Crash Energy Management," US Patents, 6,755,453 - June 29, 2004, 6,976,729 - December 20, 2005, and 7,040,658 - May 9, 2006.
24. Kellas, S., Jackson, K.E, and Littell, J.D. "Full-Scale Crash Test of an MD-500 Helicopter with Deployable Energy Absorbers." Proceedings from the 66th American Helicopter Society Annual Forum and Technology Display. Phoenix, AZ. May 11-13, 2010.
25. Littell, J.D. "Crash Test of an MD-500 Helicopter." Proceedings from the 67th American Helicopter Society Annual Forum and Technology Display. Virginia Beach, VA. May 3-5, 2011.
26. Carper, C.H. et al. "Army Helicopter Crashworthiness." Research Project, Applied Technology Laboratory, U.S. Army Research and Technology Laboratories, Fort Eustis, VA, 1983.
27. Hamada, H. et al. "Comparison of Energy Absorption of Carbon/Epoxy and Carbon/PEEK Composite Tubes." Composites Vol.12, No. 4 Pp. 245-252. July 1992.
28. Feraboli, P. et al. "Crush Energy Absorption of Composite Channel Section Specimens." Composites Part A. Vol. 40 Pp. 1248-1256. 2009.
29. Littell, J.D., Putnam, J.B., and Hardy, R.C. "The Evaluation of Composite Energy Absorbers for use in UAM VTOL Vehicle Impact Attenuation". Proceedings from the 75th American Helicopter Society Annual Forum and Technology Display. Philadelphia, PA. May 13-16, 2019.
30. Carden, H.D., Boitnott, R.L. and Fasanella, E.L. "Behavior of Composite/Metal Aircraft Structural Elements and Components under Crash Type Loads – What Are They Telling Us?" International Council of Aeronautical Sciences. Stockholm Sweden. 1990.
31. Kellas, S. and Knight, N.E. "Design, Fabrication, and Testing of Composite Energy-Absorbing Keel Beams for General Aviation Type Aircraft." NASA CR-2002-212133. December 2002.
32. Littell, J.D. et al. "The Development of Two Composite Energy Absorbers for use in a Transport Rotorcraft Aircraft Crash Testbed (TRACT 2) Full-Scale Crash Test." ASH International 71st Annual Forum & Technology Display. May 5-7, 2015. Virginia Beach, VA.
33. Kaul, A. et al. "A Revolution in Preventing Fatal Craniovertebral Junction Injuries: Lessons Learned from the Head and Neck Support Device in Professional Auto Racing." J. Neurosurgery Spine. 25:756-761. 2016.
34. Cirrus Aircraft. "Guide to the Cirrus Airframe Parachute System (CAPS)". https://cirrusaircraft.com/wp-content/uploads/2014/12/CAPS_Guide.pdf. Accessed April 19, 2019.
35. BRS Aerospace. VTOL. https://brsaerospace.com/vtol/. Accessed April 19, 2019.
36. BRS Aerospace. "WSU-NIAR to Develop Testing Protocols for BRS Aerospace Parachute Recovery Systems. Sept, 24, 2018. https://brsaerospace.com/pressrelease_09-25-2018/. Accessed April 19, 2019.
37. Uber. "Uber Elevation Mission and Vehicle Requirements." https://s3.amazonaws.com/uber-static/elevate/Summary+Mission+and+Requirements.pdf. Accessed April 19, 2019.
38. Putnam, J.B. and Littell, J.D. "Evaluation of Impact Energy Attenuators and Composite Material Designs of a UAM VTOL Concept Vehicle." Proceedings from the 75th Vertical Flight Society Annual Forum and Technology Display. Philadelphia, PA. May 13-16, 2019.

39. Johnson, W., Silva, C., and Solis, E. "Concept Vehicles for VTOL Air Taxi Operations." Proceedings from the AHS Technical Conference on Aeromechanics Design for Transformative Vehicle Flight. San Francisco, CA. January 16-19, 2018.

40. Trancend Air. “BRS and Transcend Air partner to provide VY 400 with whole-aircraft parachute.” https://www.verticalmag.com/press-releases/brs-and-transcend-air-partner-to-make-vy-400-safest-vtol-aircraft-in-history/. Accessed April 19, 2019.
41. ASTM International. “Committee F44 on General Aviation Aircraft.” https://www.astm.org/COMMIT/SCOPES/F44.htm. Accessed May 3, 2019.
42. ASTM. “Standard Specification for Emergency Conditions, Occupant Safety and Accommodations.” ASTM F3083M-18. 2018.
43. Bolukbasi, A., et al. “Full Spectrum Crashworthiness Criteria for Rotorcraft.” RDECOM TR 12-D-12. December 2011.
44. EASA. “Vertical Take-off and Landing Aircraft: Proposed Special Condition for small-category VTOL aircraft.” SC-VTOL-01. October 15, 2018.