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ORIGINAL PAPER

Crashworthiness considerations for liquid hydrogen tank integration in transport airplanes

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Abstract

This paper presents results of initial research on crashworthy liquid hydrogen (LH2) tank integration in transport airplanes. First, crashworthiness requirements and load cases are defined, and a proposal for a crashworthiness demonstration strategy is developed. Aim of this first part of the paper is to provide a potential framework of requirements, load cases, and a demonstration path that may be applied, or further developed, in future research studies. In a second part, design aspects for a crashworthy LH2 tank integration are presented and discussed on a theoretical basis. Both, the airframe and the LH2 tank, are considered in this discussion. A 2-layer safety approach is proposed that considers a crash safe LH2 tank design as a second safety layer, in addition to a crashworthy airframe design, to prevent hazardous tank leakage under more severe crash conditions when the airframe crashworthiness capacity is exceeded. Finally, an exemplary application at conceptual design level is presented in a last part of this paper. A design example for crashworthy LH2 tank integration is discussed and exemplary finite element simulation results of selected load cases at the fuselage section and full fuselage level are presented.

Keywords Energy storage crashworthiness · Liquid hydrogen storage · Transport airplane · Crash requirements · Crash load cases · Crashworthiness demonstration · Finite element simulation · LS-DYNA

1 Introduction

The introduction of transport airplanes powered by liquid hydrogen (LH2) poses significant challenges for both infrastructure and airplane design. With regard to the airplane design the LH2 tanks and systems must be safely integrated in the fuselage. In this process, the tanks must be designed to withstand not only operational flight and ground loads but also potential crash loads during an emergency crash landing without experiencing hazardous failure or hydrogen leakage. Thereby, the overall aim is to maintain at least the same level of safety as obtained for traditional airplanes. With the given energy density ratio of LH2 versus kerosene significantly larger tank volumes are required for the storage of LH2 which requires other storage solutions than the wing box structures [1]. LH2 tank installation in the rear fuselage behind the rear pressure bulkhead, the so-called 'caudal' tank configuration as depicted in Fig. 1, is one of the most promising integration solutions although other solutions are also discussed in literature [2–11]. With regard to crashworthy airplane designs such tank integration solutions must consider safe integration of LH2 tanks and systems, and additionally must consider potential effects on the overall airplane crash performance as the general airplane configuration is partly non-traditional.

Hence, to achieve mature solutions for low-emission airplane concepts based on hydrogen as energy carrier, great efforts are needed for the research and development of these new concepts.

As a basis for future research work on safety solutions, the aim of this paper is to discuss general crashworthiness aspects for the integration of LH2 tanks in transport airplanes. In a first part, in chapter 2, crashworthiness requirements are derived and load cases are defined which may be used for research applications. In addition, a crashworthiness demonstration strategy is proposed in chapter 3. In a second part, general design aspects are discussed in chapter

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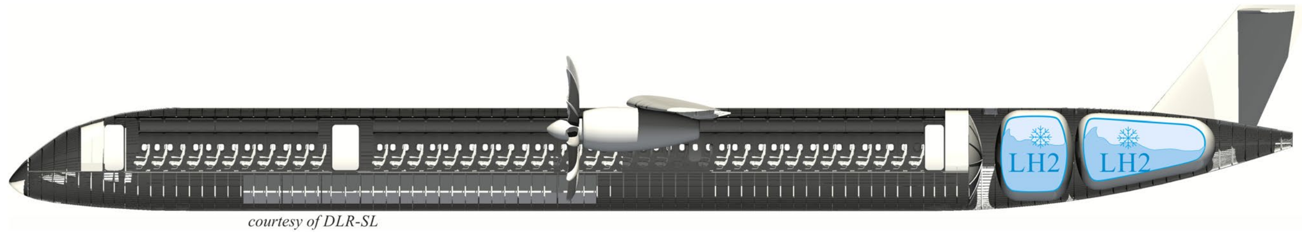

Fig. 1 Transport airplane with 'caudal' LH2 tank installations in the rear fuselage

4 and a specific 2-layer safety approach is proposed in chapter 5. Examples are presented in chapter 6.

The basis of the presented work is a 'caudal' tank integration of two LH2 tanks in the rear fuselage, however most of the aspects discussed can be transferred to any tank integration solution.

2 Crashworthiness requirements and load cases for research applications

The integration of large LH2 tanks in transport airplanes is not yet subject of current certification specifications. The regulatory framework of EASA's CS-25 or FAA's 14 CFR Part 25 is focused on traditional fuel tank integration [12, 13]. For this reason, initial research work concentrated on the definition of requirements that may be used in the scope of research work.

Crashworthiness requirements for the integration of LH2 tanks are generally related to the field of 'energy storage crashworthiness'. In contrast, typical requirements known from 'structural crashworthiness' are focused on the cabin area of an airplane fuselage and aim to prevent occupant injuries by defining requirements such as to maintain a survivable volume, to limit occupant loads, or to maintain emergency egress paths [14–16]. Concerning 'energy storage crashworthiness', the main focus is on preventing any post-crash hazards related to the energy storage [17–19]. From both categories, 'energy storage crashworthiness' and 'structural crashworthiness', the following two overall requirements can be seen as the most relevant safety aspects for LH2 tank integration with the focus on a caudal tank configuration:

(a) Tank leakage: Prevent hazardous conditions caused by tank leakage, in terms of risk of a post-crash fire but also risks originating from the cryogenic condition of the stored hydrogen that may get in contact with occupants or people on the ground.
(b) Mass retention: Prevent hazardous conditions caused by breaking loose of large items of mass, in terms of large LH2 tanks installed behind the cabin.

For a detailed definition of requirements, literature from past research work as well as existing regulatory specifications were reviewed. Past research work on crash resistant fuel tanks was evaluated as valuable sources [19–26] as most of these aspects can directly be transferred to LH2 tank applications. Besides those existing requirements, the identification of novel aspects, specifically for LH2 tank integration, can be supported by the definition of 'cause and effect' relationships based on representative accident data, as done in the past for fuel tank safety [19]. Thereby, the intent is to capture all involved structures and failures for which design solutions are required to minimize the risk of post-crash hazards. Figure 2 illustrates such a 'cause and effect' relationship, the highlighted example is relevant also for LH2 tank integration in the rear fuselage. In a crash event, a main gear collapse (cause) can lead to fuselage impact which can result in fuselage break (effect) and finally the loss of LH2 tank integrity (hazardous consequence).

From the 'cause and effect' evaluation, fuselage break was identified as the most critical novel aspect as full loss of fuselage-installed LH2 tanks' integrity is at high risk in case fuselage break occurs at tank installation zones. In contrast, traditional fuel tanks installed in the wing structure are outside of typical fuselage break zones [27].

The review of regulatory specifications first considered the certification specifications for large airplanes, EASA CS-25 [12]. Energy storage related requirements were taken and transferred to the LH2 tank application. It is expected that authorities will publish Special Conditions (SC) Crashworthiness for the integration of LH2 tanks in transport airplanes. Therefore, existing SCs and means of compliance (MOC) dealing with crashworthiness requirements were additionally reviewed [14–16, 28–32]. In addition, working group recommendations were considered for the selection of vertical impact velocities used for compliance demonstration [33]. Strong relevance for LH2 tank integration was found in EASA's special condition for a rear centre fuel tank that is installed in the fuselage directly behind the wing box [28]. In this regulatory document, aspects are discussed that consider fuselage break points, sliding on the ground, the need for compliance demonstration by a fuel tank integrity drop test as well as the substantiation of a vertical descent velocity based on full airplane considerations. In this special

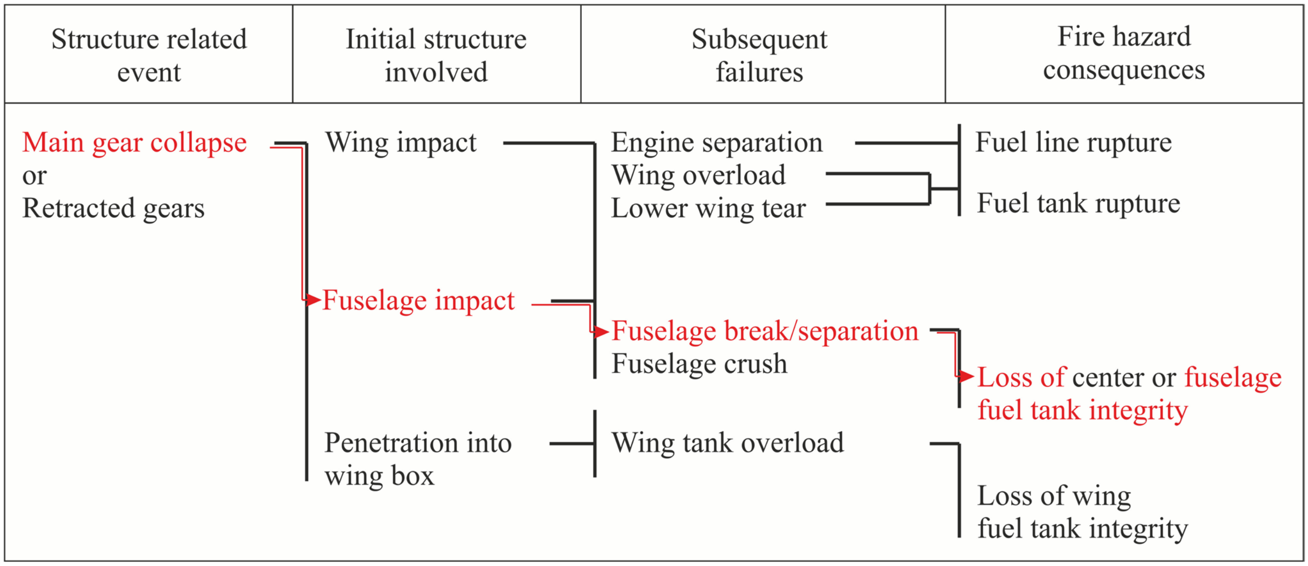

Fig. 2 'Cause and effect' relationship considering accident events which lead to a fire hazard, based on [19]

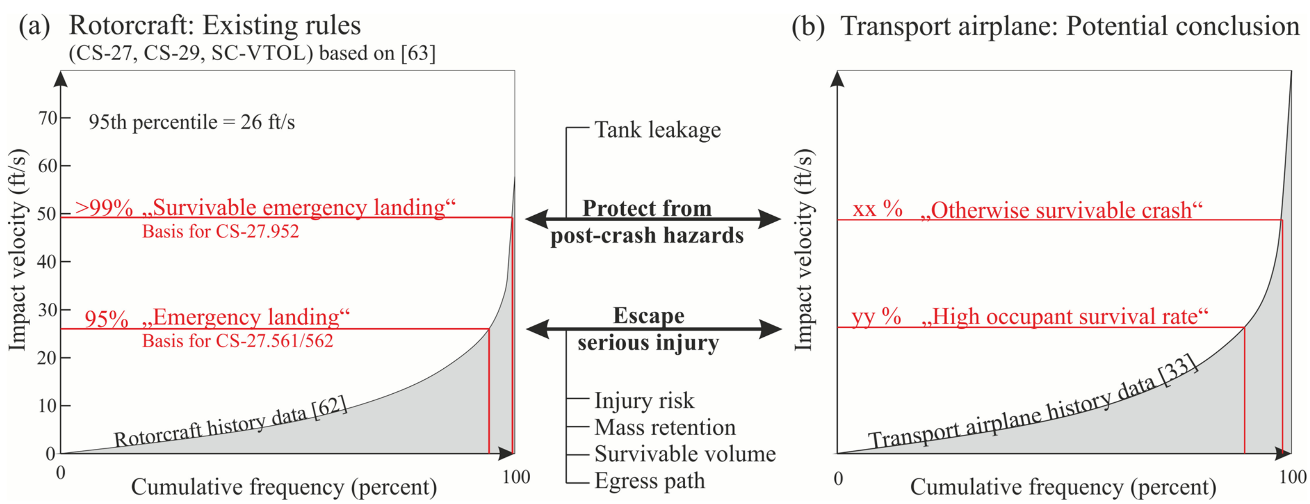

Fig. 3 **a** Existing certification rules for rotorcraft versus **b** Conclusion drawn for transport airplanes based on published special conditions

condition, a new term is introduced: the 'otherwise survivable crash', which is defined as a condition beyond the emergency landing conditions specified in CS-25.963(d)(4) and for which the demonstrated level of occupant survivability may be substantially exceeded in many sections of the fuselage, but not necessarily all [28]. Previous special conditions with the focus on structural crashworthiness defined the term 'high occupant survival rate' for the demonstration of escaping serious injuries [15, 16]. As a conclusion, both terms can be taken to draw a schema for transport airplanes similar to existing rules for rotorcraft which provide already more advanced energy storage crashworthiness requirements [34–36], as depicted in Fig. 3. For transport airplanes, the specific impact velocity respectively the specific percentiles, see Fig. 3, should be selected dependent on the fuselage size for which valuable information is given in [33, 37, 38].

The review of past research work as well as existing regulatory specifications is summarized in Table 1 in terms of detailed requirements which may be used for research work on crashworthy LH2 tank integration in transport airplanes.

The above discussed literature was additionally reviewed to derive load cases for the investigation respectively demonstration of crashworthiness. A summary is presented in Table 2 where different crash load cases are proposed for demonstration of compliance with the requirements defined in Table 1. While 'minor crash landing' load cases are mainly based on the existing CS-25 regulation [12], the load cases beyond minor crash landing consider various existing special conditions [14–16, 28] as well as further aspects and candidate scenarios based on past research work and

Table 1 Proposed crashworthiness requirements for research work on LH2 tank integration

Category		Requirement	Definition	Loading condition	Relevance
Mass retention	All items of mass	LH2-Req.#1	LH2 tanks and LH2 systems, as well as other large items of mass must be designed to withstand the specified ultimate inertia forces of CS-25.561(b)(3); deformation of LH2 tanks and LH2 systems, however, is allowed according to CS-25.561(d) as soon as a rapid evacuation is not affected. (based on: CS-25.561)	LH2-LC #1: CS-25.561(b)(3) ultimate inertia forces	High
Hazardous LH2 leakage	As a result of breaking loose of system	LH2-Req.#2	The landing gear system must be designed so that when it fails due to overloads during take-off and landing, the failure mode is not likely to cause hazardous LH2 leakage. (based on: CS-25.721(a))	LH2-LC #2:CS-25.721 (a) landing gear failure	Low. However, separated landing gear may impact areas where LH2 tanks or systems are installed
Hazardous LH2 leakage	As a result of wheels-up landing	LH2-Req.#3	The airplane must be designed to avoid any rupture leading to hazardous LH2 leakage as a result of a wheels-up landing on a paved runway. (based on: CS-25.721(b))	LH2-LC #3: CS-25.721(b)(1) minor crash landing LH2-LC #4:CS-25.721(b)(2) sliding on tne ground	High
Hazardous LH2 leakage	As a result of breaking loose of system	LH2-Req.#4	For configurations where the engine nacelle is likely to come into contact with the ground, the engine pylon or engine mounting must be designed so that when it fails due to overloads (assuming the overloads to act predominantly in the upward direction and separately predominantly in the aft direction), the failure mode is not likely to cause hazardous LH2 leakage. (based on: CS-25.721(c))	LH2-LC #5: CS-25.721(c) engine pylon/ engine mounting failure	Low. However, separated engine pylon or engine mounting may impact areas where LH2 tanks or systems are installed
Mass retention	Mass item that would penerate LH2 tanks/lines	LH2-Req.#5	Each stowage compartment must be designed (…) to the specified flight and ground load conditions and, where the breaking loose of the contents of such compartments could (…) penetrate LH2 tanks or lines or cause fire or explosion or other hazard by damage to adjacent systems, to the emergency landing conditions of CS 25.561(b)(3). (based on: CS-25.787(a) Stowage compartments)	LH2-LC #1: CS-25.561(b)(3) ultimate inertia forces	Low. LH2 tanks are typically installed far away from stowage compartments and LH2 pipes installed outside of the airframe
Hazardous LH2 leakage	In otherwise survivable emergency landing conditions	LH2-Req.#6	LH2 tanks tanks must (…) be designed, located and installed so that no LH2 is released in or near the fuselage or near the engines in quantities sufficient to (i) start a serious fire or (ii) to injure occupants in otherwise survivable emergency landing conditions LH2-Req. and: LH2 tanks must be able to resist rupture and to retain its content (1) under ultimate hydrostatic design conditions and (2) for wing LH2 tanks near the fuselage or near the engines under specified fuel pressures. (based on: CS-25.963(d)(1) and (2))	LH2-LC #8: otherwise survivable emergency landing conditions LH2-LC #6: CS-25.963(d)(1) ultimate hydrostatic design conditons LH2-LC #7: CS-25.963(d)(2) fuel pressures	High
Hazardous LH2 leakage	LH2 tank; as a result of wheels-up landing	LH2-Req.#7	For each LH2 tank and surrounding airframe structure, the effects of crushing and scraping actions with the ground should not cause hazardous LH2 leakage, or generate temperatures that would constitute a fire hazard under the conditions specified in CS 25.721(b). (based on: CS-25.963(d)(4))	LH2-LC #3: CS-25.721(b)(2) minor crash landing LH2-LC #4: CS-25.721(b)(2) sliding on the ground	High

Table 1 (continued)

Category		Requirement	Definition	Loading condition	Relevance
Hazardous LH2 leakage	LH2 tank; as a result of breaking loose of system	LH2-Req.#8	LH2 tank installations must be such that the tanks will not rupture as a result of an engine pylon or engine mount or landing gear, tearing away as specified in CS 25.721(a) and (c). (based on: CS-25.963(d)(5))	LH2-LC #2: CS-25.721(a) landing gear failure LH2-LC #5: CS-25.721(c) engine pylon/ engine mounting failure	Low. However, separated systems may impact areas where LH2 tanks or systems are installed
Hazardous LH2 leakage	LH2 system; as a result of wheels-up landing	LH2-Req.#9	LH2 system components in an engine nacelle or in the fuselage must be protected from damage which could result in hazardous LH2 leakage as a result of a wheels-up landing on a paved runway under each of the conditions prescribed in CS 25.721(b). (based on: CS-25.994)	LH2-LC #3: CS-25.721(b)(1) minor crash landing LH2-LC #4: CS-25.721(b)(2) sliding on the ground	High
Hazardous LH2 leakage	Fuselage break	LH2-Req.#10	Demonstrate that when fuselage failure or rupture happens, this does not occur in the area where the LH2 tanks are installed. (based on: EASA SC-E25.963–01)	LH2-LC #10: EASA SC-E25.963–01 different impact conditions at airplane level	High
Hazardous LH2 leakage	LH2 tank integrity	LH2-Req.#11	When the fuselage section that contains the LH2 tanks is subjected to an impact condition with a vertical descent velocity, the LH2 tanks should not experience hazardous LH2 leakage. LH2-Req. This should be demonstrated via a LH2 tank integrity drop test or #11 analysis supported by test evidence (…). Pass/failure criteria is the demonstration of no leakage that could constitute a fire hazard or any other hazard caused by the cryogenic liquid. (based on: EASA SC-E25.963–01)	LH2-LC #11: EASA SC-E25.963–01 the fuselage section drop test respectively analysis must be performed for "various fuel states" and "various payload states"	High
Injury prevention	Effects on airframe sections with cabin installations	LH2-Req.#12	LH2 tank integration may significantly change the airframe crash LH2-LC #11: characteristic. It must be demonstrated that the LH2 tank integration has no negative effect on the crash performance of occupied fuselage sections. The following key crashworthiness parameters may apply: Retention of items of mass Maintenance of acceptable acceleration and loads experienced by the occupants Maintenance of a survivable volume Maintenance of occupant emergency egress path (based on: New, proposed requirement.)	LH2-LC #11: Fuselage section drop test respectively analysis must be performed for various payload states LH2-LC #10: Airplane level analysis must be performed for various loading conditions	High
Hazardous LH2 leakage	As a result of sliding on the ground	LH2-Req.#13	Sliding on the ground should not lead to damage that would result in hazardous LH2 leakage. (based on: EASA SC-E25.963–01)	LH2-LC #12: EASA SC-E25.963–01 sliding on the ground following an airplane impact beyond minor crash landing	High

accidents [19, 39–45]. Three general load case scenarios are defined, as specified in [28]:

(a) Fuel tank integrity drop test at fuselage section level
(b) Crash impact at airplane level
(c) Sliding on the ground at airplane level

The fuel tank integrity drop test is mainly intended for the investigation of the crash energy absorption management and the crash kinematics. Vertical impact speeds are defined stepwise up to a maximum value ($v_{z\_max\_local}$) which corresponds to the maximum local impact velocity of the LH2 tank's fuselage section determined based on airplane level analysis of representative accident scenarios. The range of impact velocities as well as impact energies are defined to ensure the crash concept performs sufficiently well under all impact energies up to a specified maximum. Robustness can be considered by variations of pitch and roll angle as well as different impact terrain.

Table 2 Proposed crash load cases for research work on LH2 tank integration

Categories			Load case	Vz	Vx	LG config	A/C mass	Payload (pax / cargo)	Fuel states	Pitch angle	Roll angle	Yaw angle	Terrain	Obstacles
Fuel tank integrity drop test (Fuselage section drop test)	Beyond minor crash landing	Various impact speeds	LC#11(x)	5 ft/s	-	-	-	100% / 100%	100%	0°	0°	-	hard	-
			LC#11(x)	10 ft/s	-	-	-	100% / 100%	100%	0°	0°	-	hard	-
			LC#11(x)	15 ft/s	-	-	-	100% / 100%	100%	0°	0°	-	hard	-
			LC#11(x)	20 ft/s	-	-	-	100% / 100%	100%	0°	0°	-	hard	-
			…	…	-	-	-	100% / 100%	100%	0°	0°	-	hard	-
			LC#11(x)	Vzmax_local	-	-	-	100% / 100%	100%	0°	0°	-	hard	-
		Various impact energies	LC#11(x)	Vzmax_local	-	-	-	100% / 100%	75%	0°	0°	-	hard	-
			LC#11(x)	Vzmax_local	-	-	-	100% / 100%	50%	0°	0°	-	hard	-
			LC#11(x)	Vzmax_local/2	-	-	-	50% / 0%	50%	0°	0°	-	hard	-
		Robustness	LC#11(x)	Vzmax_local	-	-	-	100% / 100%	100%	3.5°	0°	-	hard	-
			LC#11(x)	Vzmax_local	-	-	-	100% / 100%	100%	7°	0°	-	hard	-
			LC#11(x)	Vzmax_local	-	-	-	100% / 100%	100%	0°	5°	-	hard	-
			LC#11(x)	Vzmax_local	-	-	-	100% / 100%	100%	0°	10°	-	hard	-
			LC#11(x)	Vzmax_local	-	-	-	100% / 100%	100%	0°	0°	-	soft soil	
Airplane level crash impact	Minor crash landing	Minor crash landing	LC#3(i)	5 ft/s	1.25 VSO	fully retracted	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
			LC#3(ii)	5 ft/s	1.25 VSO	FWD LG not extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
			LC#3(ii)	5 ft/s	1.25 VSO	MLG left not extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
	Beyond minor crash landing	Vzmax crash landing	LC#10(x)	Vzmax_global	1.25 VSO	fully retracted	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
			LC#10(x)	Vzmax_global	1.25 VSO	FWD LG not extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
			LC#10(x)	Vzmax_global	1.25 VSO	MLG left not extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
		Various impact speeds	LC#10(x)	Vzmax_global	1.25 VSO	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
			LC#10(x)	20	1.25 VSO	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
			LC#10(x)	10	1.25 VSO	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
		Robustness	LC#10(x)	Vzmax_global	1.25 VSO	fully extended	MTOW	100% / 100%	100%	3.5°	0°	0°	hard	-
			LC#10(x)	Vzmax_global	1.25 VSO	fully retracted	MLW	100% / 100%	100%/ acc. to MLW	0°	0°	0°	hard	-
			LC#10(x)	Vzmax_global	1.25 VSO	fully extended	MLW	100% / 100%	100%/ acc. to MLW	7°	0°	0°	hard	-
			LC#10(x)	Vzmax_global	1.25 VSO	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	5°	0°	hard	-
			LC#10(x)	Vzmax_global	1.25 VSO	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	10°	0°	hard	-
			LC#10(x)	Vzmax_global	1.25 VSO	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	10°	hard	-
			LC#10(x)	Vzmax_global	1.25 VSO	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	20°	hard	-
			LC#10(x)	Vzmax_global	1.25 VSO	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	soft soil	-
		Slope impact	LC#10(x)	Vzmax_global	1.25 VSO	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard; 10° initial slope	
			LC#10(x)	Vzmax_global	1.25 VSO	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard; 30° initial slope	
			LC#10(x)	Vzmax_global	1.25 VSO	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard; 10° slope	
			LC#10(x)	Vzmax_global	1.25 VSO	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard; 30° slope	
		Fuselage break	LC#10(x)	Vzmax_global	0	fully retracted	MLW	100% / 100%	100%/ acc. to MLW	0°	0°	0°	stepped terrain	
Airplane level sliding on the ground	Minor crash landing	Sliding on the ground	LC#4(i)	5 ft/s	VSO	fully retracted	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
			LC#4(i)	5 ft/s	VSO	fully retracted	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	10°	hard	-
			LC#4(i)	5 ft/s	VSO	fully retracted	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	20°	hard	-
			LC#4(ii)	5 ft/s	VSO	FWD LG not extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
			LC#4(ii)	5 ft/s	VSO	MLG left not extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
		LG failure	LC#2(x)	5 ft/s	VS0	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	loss of LG
			LC#2(x)	5 ft/s	VS0	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	10°	hard	loss of LG
		Engine failure	LC#5(x)	5 ft/s	VS0	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	loss of engine
			LC#5(x)	5 ft/s	VS0	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	10°	hard	loss of engine
	Beyond minor crash landing	Sliding on the ground	LC#12(x)	Vzmax_global	VSO	fully retracted	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
			LC#12(x)	Vzmax_global	VSO	fully retracted	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	10°	hard	-
			LC#12(x)	Vzmax_global	VSO	fully retracted	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	20°	hard	-
			LC#12(x)	Vzmax_global	VSO	FWD LG not extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
			LC#12(x)	Vzmax_global	VSO	MLG left not extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	-
		LG failure	LC#12(x)	Vzmax_global	VS0	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	loss of LG
			LC#12(x)	Vzmax_global	VS0	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	10°	hard	loss of LG
		Engine failure	LC#12(x)	Vzmax_global	VS0	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard	loss of engine
			LC#12(x)	Vzmax_global	VS0	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	10°	hard	loss of engine
		Slope	LC#12(x)	Vzmax_global	VS0	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard; 10° positive slope	
			LC#12(x)	Vzmax_global	VS0	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard; 30° positive slope	
			LC#12(x)	Vzmax_global	VS0	fully extended	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	hard; 30° negative slope + 50 ft runway elevation	
		Terrain	LC#12(x)	Vzmax_global	VS0	fully retracted	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	rocky terrain	
			LC#12(x)	Vzmax_global	VS0	fully retracted	MLW	100% / 100%	100%/ acc. to MLW	3.5°	0°	0°	with obstacles	

Vzmax_local: max. local impact speed at fuselage section that contains the energy storage (can be higher or lower than Vzmax_global depending on airplane crash kinematics)
Vzmax_global: max. impact speed of airplane c.g. (to be selected according to crash capacity of equivalent traditional airplanes; dependent on airplane size)
VSO: stall speed; acc. to AMC25.963(d): A reasonable attitude should be selected within the speed range from VL1 to 1.25 VL2 based upon the fuel tank arrangement.
LG: landing gear
FWD LG: forward landing gear
MLG: main landing gear
A/C: aircraft
pax: passenger
MLW: maximum landing weight
MTOW: maximum take-off weight

The crash impact at airplane level considers different landing gear configurations for minor crash landing as well as for crash landings up to the maximum vertical impact speed (v_{z_max}). Those conditions can lead to the release of mass items or to fuselage break which are risks for the loss of tank integrity. Again, robustness can be considered by variations of pitch, roll, and yaw angles as well as different impact terrain. In addition, and based on past research work [45] as well as accident data [43], impact into sloped terrain can be considered.

Sliding on the ground at airplane level is considered for minor crash landing as well as beyond minor crash landing up to the maximum vertical impact speed (v_{z_max}). After crash impact and during subsequent sliding on the ground the landing gear and the engines may be at risk to separate and impact the rear fuselage with the LH2 tanks installed. Also based on accident data, sliding on sloped terrain is considered [44, 46]. Referring to historical crash resistant fuel tank aspects [19, 42], rocky terrain as well as terrain with obstacles can also be considered as load cases for demonstration of robust energy storage crashworthiness.

In addition to the load cases presented in Table 2, further load cases in terms of horizontal acceleration-time pulses may be considered for investigation and demonstration of mass retention requirements at the fuselage section level. As an example, using finite element simulation representative horizontal crash acceleration pulses may be applied on a rear fuselage section model with LH2 tank installation to investigate load limiter solutions that are intended to prevent the tanks from breaking loose.

3 Proposal for a crashworthiness demonstration strategy

An established demonstration strategy for structural crashworthiness describes a classical building block approach with increasing structural complexity from coupon level up to full-scale level [47]. Physical as well as virtual testing is considered, while the virtual simulation is embedded in a so-called modelling and simulation credibility assurance framework [48, 49]. Virtual simulation can expand the physical test parameter space, e.g. crash load cases as defined in Table 2, can contribute to deeper insights in structural effects, and may enable the demonstration of large-scale levels solely by virtual simulation.

The classical building block for structural crashworthiness was taken as basis for the development of a demonstration strategy for crashworthy LH2 tank integration, which is depicted in Fig. 4. This proposed building block consist of

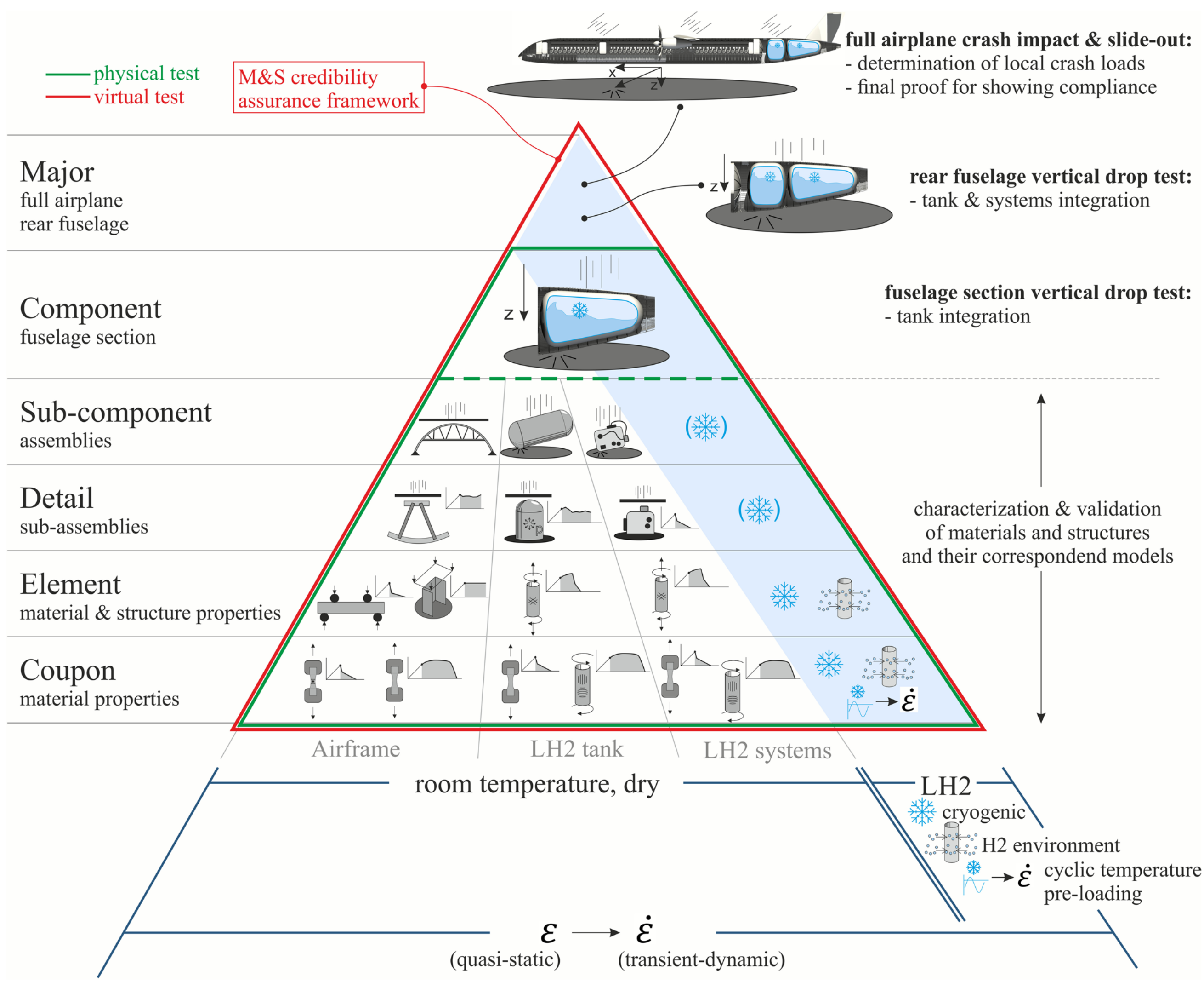

Fig. 4 Proposed building block for demonstration of crashworthy LH2 tank integration

three columns: airframe, LH2 tank, and LH2 systems. All three categories contribute to energy storage crashworthiness and must be considered in a demonstration strategy. Throughout the building block levels, LH2 specific aspects need to be considered. These aspects are (a) the cryogenic temperature that may affect material behaviour and may also lead to temperature expansion effects, (b) the hydrogen environment that can change material properties e.g. due to hydrogen embrittlement, and (c) cyclic temperature preloading during normal operation that may initiate microcracks in materials with consequences for the material's performance under crash conditions [50, 51]. While all three aspects need to be considered at coupon level, higher building block levels may not necessarily consider the hydrogen environment and cyclic-temperature pre-loading aspects as those effects might be captured by reasonable definition of material allowables.

At the higher structural levels, the proposed building block specifies component, major, and full-airplane testing, with the component test as highest level considered for physical testing. At component level, the fuel tank integrity drop test, as discussed in chapter 2, is defined with a test article that describes a fuselage section with installed LH2 tank. The investigation of the general energy absorption management and crash kinematics shall specifically demonstrate that the design is capable of limiting tank accelerations, preventing tank intrusions, and limiting tank deformations. At major level, the entire rear fuselage including the rear pressure bulkhead is considered and applied to purely vertical crash impact. The investigation at that level is focused on the interaction of LH2 tanks, LH2 systems, and airframe. Also, potential concepts for well-directed fuselage break manipulation as well as potential interaction with cabin safety might be investigated already at this level. The full-airplane level is proposed for consideration of two aspects. First, full-airplane analysis can be used to determine local fuselage impact velocities at LH2 tank installation zones, which may significantly differ from airplane level impact conditions due to slap-down or other effects that can occur. Second, full-airplane analysis can be used as final proof for showing compliance with the given requirements. Crash interactions between typical fuselage with cabin installations and rear fuselage with LH2 tank installations can be investigated. And with regard to real-world crash environments the full-airplane analysis enables the consideration of realistic crash impact conditions with combined horizontal/vertical impact velocities, different impact attitudes, as well as crash impact and sliding on the ground with different terrain.

4 General design aspects

In this chapter, general design aspects for LH2 tank integration are discussed with the focus on crashworthiness.

As shown in Fig. 5, for redundancy reasons, at least two separate LH2 tanks must be installed in a transport airplane although the tank sizes may be different. The general tank design can be an integral or non-integral solution. In the context of this paper, the non-integral tank design is considered, hence airframe and LH2 tanks have separate structures. Thermal insulation is a key to minimize hydrogen boil-off. High vacuum combined with multi-layer insulation is the preferred solution with regard to minimizing thermal conductivity, however other insulation methods like foam, perlite, or aerogel are also discussed and partly preferred due to less system complexity [1, 9]. Vacuum insulation, which is focused in this discussion, is realized by the combination of an inner and an outer tank. The inner tank, exposed to cryogenic temperatures, can be assumed as load carrying tank structure with regard to loads introduced by the LH2 mass, the tank pressure, or dynamic sloshing effects. The outer tank maintains the vacuum insulation and hence may be equipped with ribs or other reinforcements. The LH2 systems, mainly cryogenic pumps and valves, must be located close to the tank but should be located outside the tank for accessibility reasons. The system installation can be assumed in an insulated cold box, hence a mass item, that is directly attached to the tank structure, see Fig. 5. The large LH2 tank installed in the fuselage requires a structural decoupling from airframe deformations to prevent LH2 tank loading caused by fuselage deformations during normal operation. Hence, an isostatic support, or at least a tank installation close to isostatic conditions, is required. Finally, a limited tank lifetime is expected and requires solutions for tank replacement. Large structural openings in the fuselage must be foreseen to enable the tank replacement.

With regard to crashworthiness, the two aspects (a) structural decoupling and (b) large structural openings can be seen as most relevant novel aspects to be considered in the crash design. The structural decoupling through an isostatic support of the LH2 tank is a generally unfavourable tank integration solution for ensuring crash safety as the tank supports are minimized in terms of support number and degrees of freedom, and are concentrated to fewest possible locations. Hence, risk of breaking loose under crash loading is high and complementary support solutions for crash conditions may be necessary. With regard to large structural openings, the overall fuselage crash kinematics may be affected due to those local changes in stiffness of the fuselage shell structure. The crash design may consider the required large structural openings to enforce potential

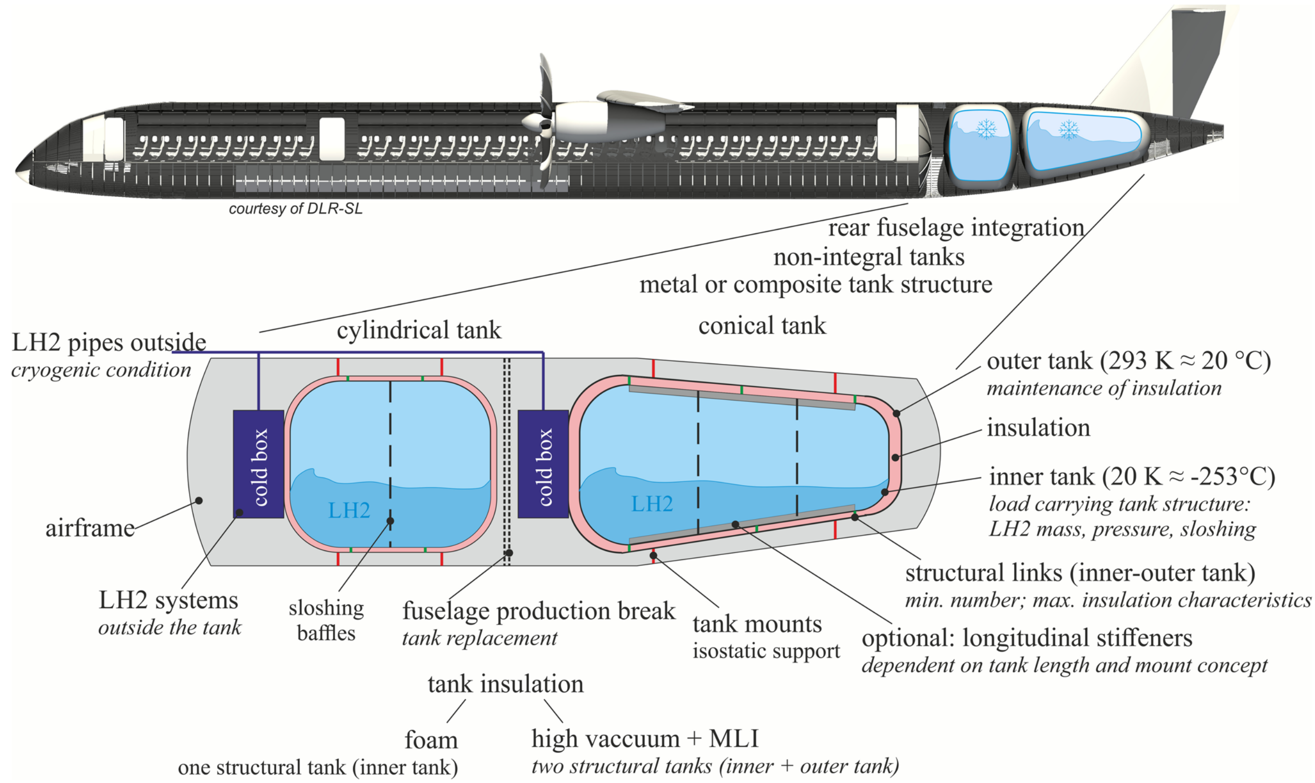

Fig. 5 Design aspects for LH2 tank integration in transport airplanes

v_{z_impact}	Tank allowable: Vertical acceleration 50g	30g	20g	10g	6g
30 ft/s (9.1 m/s)	84 mm	141 mm	211 mm	422 mm	703 mm
35 ft/s (10.7 m/s)	117 mm	155 mm	292 mm	584 mm	973 mm

Min. required stroke
(assuming ideal absorber force-displ. characteristics)
Reasonable tank allowable? → ← Reasonable required stroke?

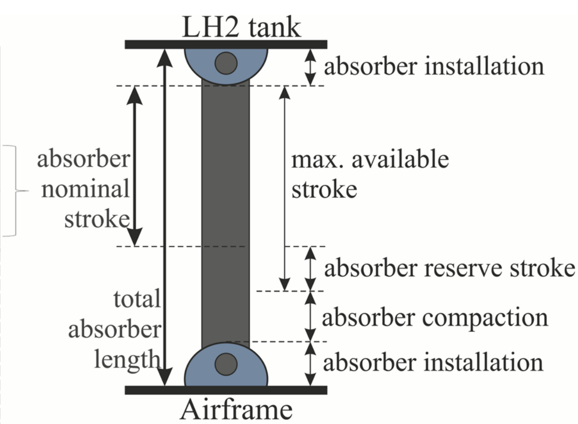

Fig. 6 LH2 tank allowable as main crash design driver

fuselage break at locations outside the LH2 tank installation zones.

When considering the LH2 tank as a system installation, the tank allowables, more precisely the maximum allowed tank acceleration, can be a main crash design driver. Taking the tank as a system designed for existing certification specifications would result in a maximum downward acceleration of 6 g according to CS-25.561. Assuming ideal airframe load attenuation at constant acceleration and a vertical impact velocity between 30–35 ft/s (9.1–10.7 m/s) the minimal required crash stroke is between 703–973 mm, see Fig. 6. With that minimum stroke, the total height of the airframe load attenuation structure can be assumed in the range of 1000 mm. Considering an airframe with exemplary fuselage diameter of 6 m, and as theoretical limit the same tank diameter, a required crash distance of 1000 mm would decrease the tank diameter to 5 m and hence reduce the tank volume by 30%. This discussion clarifies that the LH2 tanks as system installations must be included in the crash design process and reasonable tank allowables clearly beyond the 6 g downward accelerations are expected as optimum. In a crash design process, the global optimum should be identified between maximum allowed tank acceleration, hence structural tank mass, and required crash stroke respectively unused airframe volume. A higher mass penalty for the tank structure may be preferable as a reduced crash stroke significantly saves mass due to better utilization of the airframe volume for LH2 storage. An external load attenuation structure, installed underneath the fuselage shell structure, may be an alternative solution. However, other drawbacks in the overall airplane design process, such as aerodynamic drag considerations or requirements for ground clearance to prevent tail strikes, can prevent this solution.

5 Proposal of a 2-layer safety approach

Based on the discussion on general design aspects in chapter 4, a 2-layer safety approach is proposed as a reasonable strategy to provide maximum occupant survivability.

Layer (1) considers a crashworthy tank integration and is related to the airframe structure and the tank mount concept. The tank shall be embedded in the airframe in a safe way. To prevent tank leakage, sufficient crash stroke must be provided to limit the tank accelerations, a proper tank surrounding structure must be designed to prevent local tank intrusions, and proper crash kinematics must be ensured to prevent mechanical tank deformations. Regarding mass retention, robust tank mount solutions must be designed capable of sustaining longitudinal crash loads after first crash impact.

Layer (2) considers a crashworthy tank structure and is related to the tank itself. In case layer (1) capacities are exceeded in severe crash scenarios, hazardous tank leakage shall be prevented even if the tank is exposed to high accelerations, global tank deformations, or local penetration loads.

Examples for layer (1) design aspects are the definition of crash load paths. As discussed in chapter 4, an isostatic tank support required for normal operation may be an unfavourable design solution for crash due to the risk of breaking loose. A secondary crash load path may be a complementing design solution, see Fig. 7. Under normal operation, the tank is isostatically supported and decoupling from airframe deformation is ensured. In case of crash, lower airframe

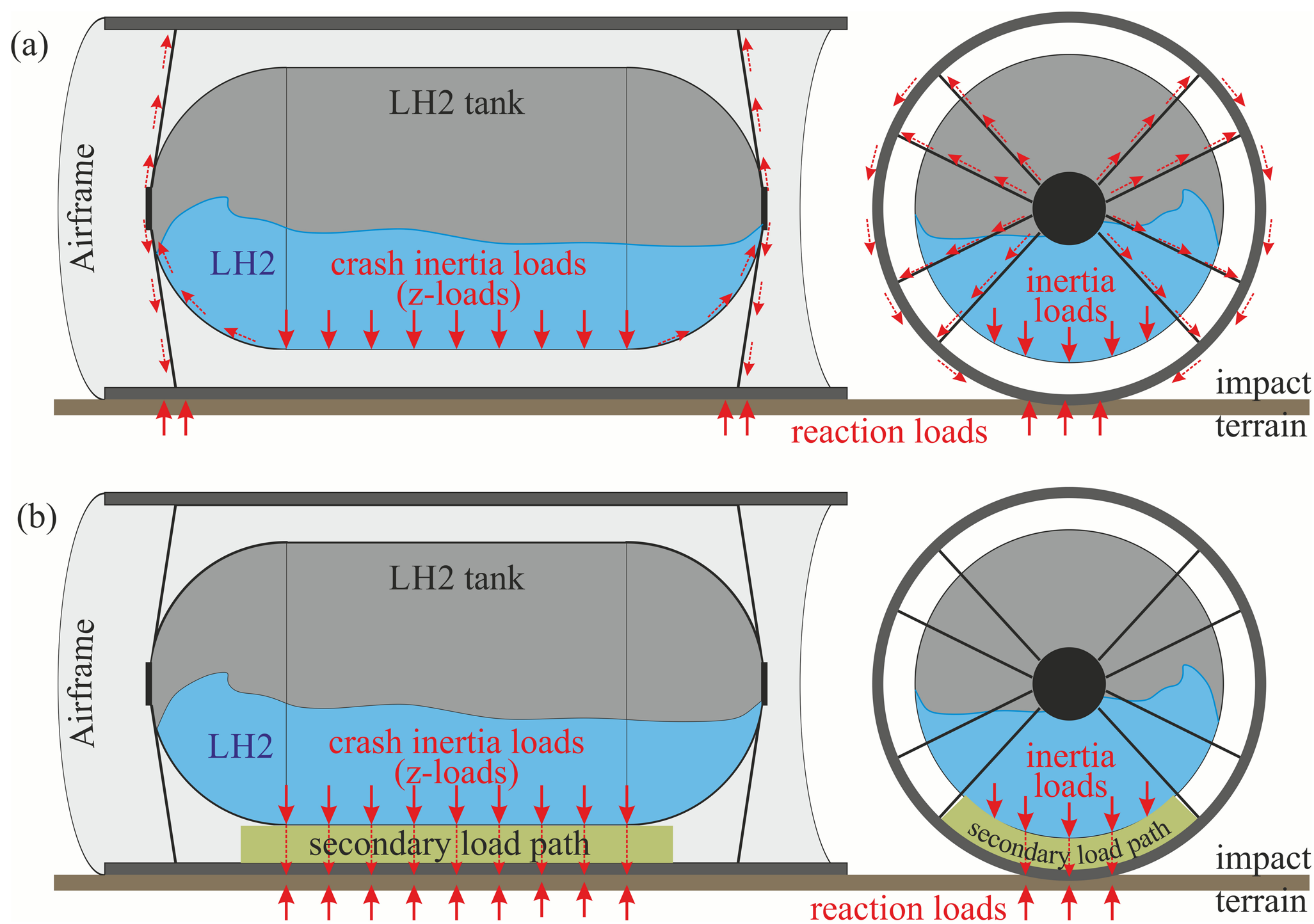

Fig. 7 Layer (1): Crash load paths. **a** Primary crash load path only, with unfavourable load transfer. **b** Secondary load path in case of crash, due to airframe deformation and corresponding contact interaction, provides favourable load transfer

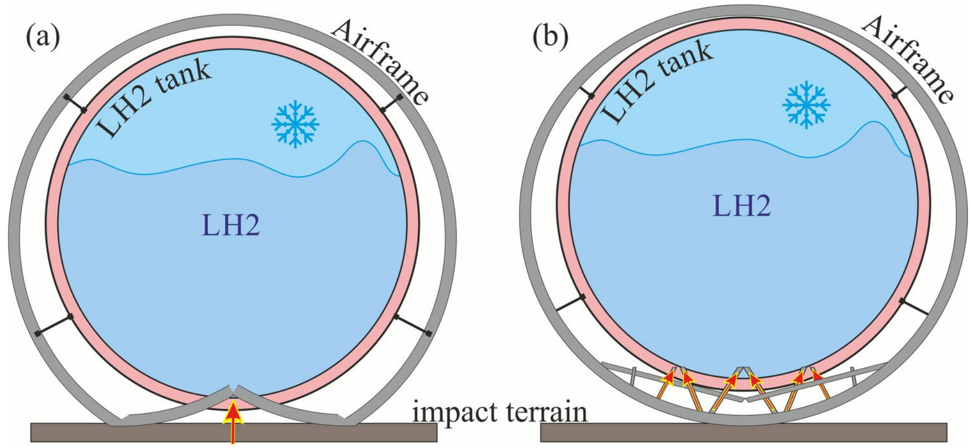

Fig. 8 Layer (1): Risk of tank penetration caused by unfavourable airframe design. **a** Penetration by lower fuselage shell. **b** Penetration by framework struts

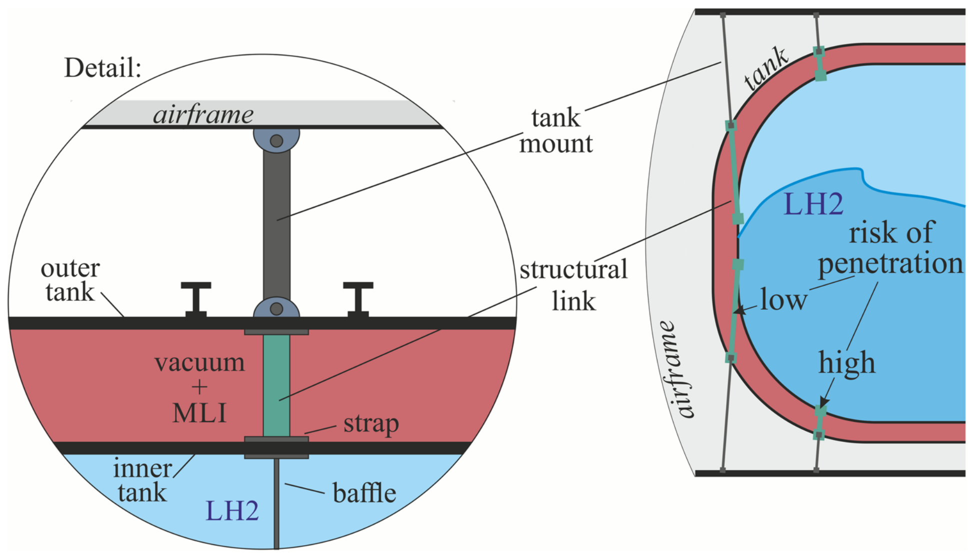

Fig. 9 Layer (2): Structural link design to prevent tank penetration

deformation lead to direct contact between the LH2 tank and the airframe load attenuation structure below. A direct load path is given and crash inertia loads of the tank can directly be transferred to the crash zone. The LH2 tank is favourably embedded on the load attenuation structure and hence can sustain higher crash loads. In contrast, the absence of a secondary crash load path requires the transfer of crash loads through the isostatically arranged tank mounts and through the fuselage shell structure to the crash zone. This crash load path leads to unfavourable tank and airframe loading and results in higher risk of catastrophic failure.

Another example for layer (1) aspects is the airframe to be designed to prevent the risk of tank penetrations, see Fig. 8. The circular fuselage structure tends to fail under crash loads according to the established kinematics 'unrolling' or 'flattening', and partly in conical rear sections under frame shear failure [52, 53]. While a flattening of the lower fuselage shell structure is preferable, an unrolling kinematics would push the broken lower frame towards the tank structure leading to high risk of tank penetration, see Fig. 8(a). The airframe must be designed to obtain proper crash kinematics leading to low risk of tank penetration by the fuselage shell structure. The airframe load attenuation structure installed underneath the LH2 tank may be designed as a crushable framework structure [54–56]. Under crash loading, framework struts may disintegrate leading to high risk of tank penetration, see Fig. 8(b). Hence, the tank surrounding structure, mainly framework struts and tank mounts, must be designed to prevent risk of tank penetration in case of structural disintegration.

Examples for layer (2) aspects refer to the load carrying tank structure as well as the crash safety tank structures. The load carrying tank structure provides so-called structural links between the inner and the outer tank, see Fig. 9. A crash function in terms of load attenuation is not foreseen for the structural links for two reasons. First, the number of structural links is minimized due to the thermal insulation requirement. Second, the structural links are exposed to cryogenic temperatures for which more brittle material failure can be expected [50, 57]. The structural links must

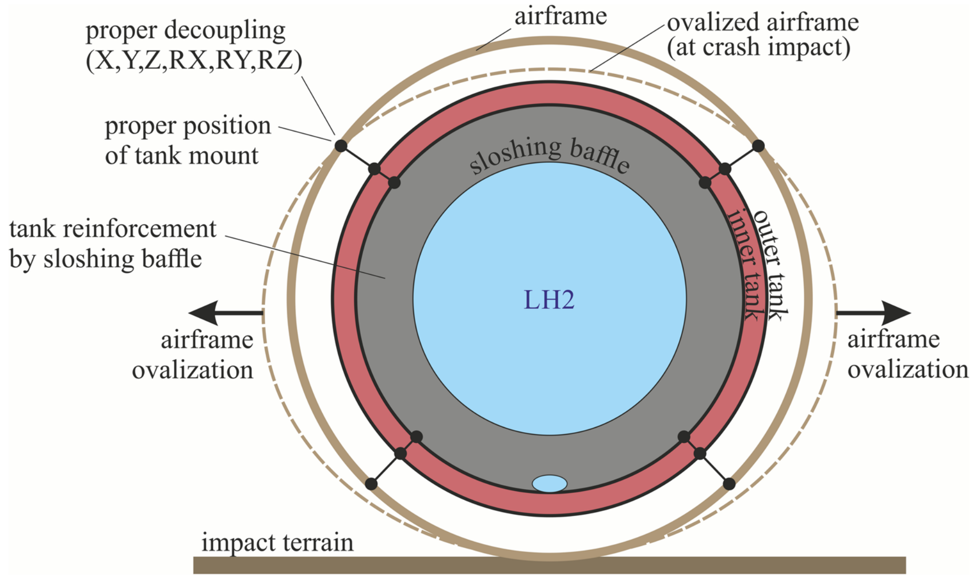

Fig. 10 Layer (2): Tank loading due to fuselage ovalization

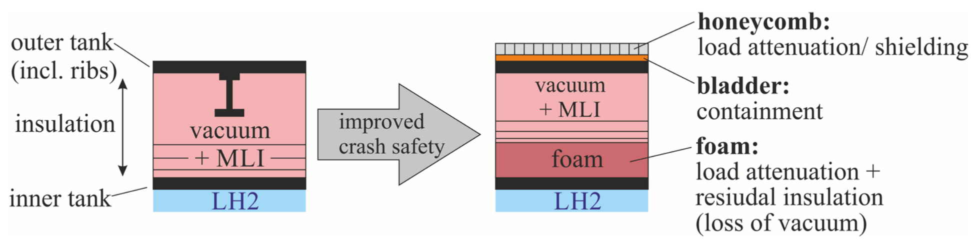

Fig. 11 Layer (2): Crash safety tank structures

be designed to prevent risk of tank penetration which can be achieved by positioning of the links quasi-tangentially to the tank surface, e.g. at the tank pole region, or by proper tank reinforcements with straps, ribs or sloshing baffles, see Fig. 9.

The load carrying tank structure may experience high loading due to ovalization of the circular fuselage cross-section in case of crash, see Fig. 10. Proper tank mount positioning and decoupling as well as the utilization of sloshing baffles for tank reinforcement may be design solutions.

Finally, mass retention of the cold box, as a large item of mass directly attached to the tank structure, is a design requirement for the tank. Breaking loose of the cold box might result in the release of a large mass item but also in disintegration of the tank and hence tank leakage.

The crash safety structures of the LH2 tank consider the inner and the outer tank, as depicted in Fig. 11. Structural ribs installed at the outer tank for stability reasons may be reasonably positioned and designed to prevent penetration effects. Additional containment means may be provided by fuel bladder concepts at the outer tank [19]. Even in case of tank rupture, containment might be given by such tank bladder solutions. Further volumetric absorbers, like honeycomb structures, at the outer tank may provide a certain load attenuation function in case of direct crash impact of the tank. With progressing absorber crushing the material densification may also provide further shielding function. A combination of load attenuation and boil-off limitation can be provided by additional foam installed between inner and outer tank, and attached to the inner tank, see Fig. 11. In case of a direct crash impact of the tank, the crushable foam provides load attenuation function for the load carrying inner tank. Furthermore, potential loss of vacuum due to damage of the outer tank can partly be compensated by the foam characteristics that provide residual insulation and hence reduce the boil-off which is a post-crash safety factor. Finally, hydrogen boil-off must be safely carried through vent pipes to exhausts far away from cabin areas and evacuation paths. Crash-safe vent pipe designs are required that provide function also in case of crash deformations. Combinations of high-strength as well as flexible vent pipes can be a design solution. Accordion-like vent pipes may provide maximum elongation capacities in case of large fuselage deformations.

Besides the above discussed examples, further design aspects for LH2 tanks may be transferred from crash-resistant fuel systems (CRFS) for transport airplanes which are based on the historical guidelines developed for rotorcraft [19, 26]. The CRFS guidelines from rotorcraft applications are summarized in Table 3. In addition, CRLH_2S guidelines for LH2 tank integration are presented in this table, which were derived from the CRFS guidelines.

Table 3 Crash-resistant energy storage system guidelines

Crash-Resistant Energy Storage System Guidelines		Crash-Resistant FUEL System (CRFS)	Crash-Resistant LH2 System (CRLH2S)
Main objectives:		- Prevent leakage	- Prevent leakage - Mass retention
Spatial Arrangement:		- Installation area relative to crash zone (tank overloading) and cabin area (mass retention) - Spatial separation of energy storage and occupants (e.g. bulkheads, vents, fire walls)	
Systems approach	Surrounding structure: Ultimate strength & failure behaviour	- Resist ultimate inertia forces and provide proper failure behaviour to prevent puncture and rupture	- Resist ultimate inertia forces and provide proper failure behaviour to prevent puncture and rupture
	Energy storage: Frangible / deformable attachment	- Design attachment to prevent rupture or local tear-out of fuel tank attachments and fuel system components	- Tank mount and surrounding airframe structure designed for mass retention and load attenuation
	Distribution system: Frangible / deformable cables & hoses	- Reinforced installation areas - (Self-sealing) breakaway couplings and mounts - Flexible / reinforced / extra long cables and hoses	- Reinforced installation areas - (Self-sealing) breakaway couplings and mounts - Flexible / reinforced / extra long cables and pipes
	Energy storage: Impact and tear resistance	- Fuel tank bladder material impact, cut and tear resistant	- Crashworthy tank design with impact, cut and tear resistance regarding true crash loads beyond CS-25.561
	Ignition source control	- Spatial separation of fuel tank and ignition sources - De-energizing / Shielding electrical sources - Inerting hot surfaces	- Crashworthy vent pipe to discharge boil off - Spatial separation of LH2 and ignition sources - De-energizing / shielding electrical sources

6 Examples

Following the theoretical discussions on crashworthiness requirements and load cases, crashworthiness demonstration strategies, and design aspects in chapter 2–5 an exemplary application at conceptual design level is presented in this chapter. Note that only exemplary load cases are presented in this chapter while for entire crash concept developments it is recommended to consider the proposed load cases discussed in chapter 2 for ensuring robust design redundancy and adequate crash performance under varied crash scenarios. In addition, the vertical impact velocity of $v_{z\_max\_local}=30$ ft/s (9.1 m/s), selected for the presented examples, should not be interpreted as a general view on the selection of proper vertical impact conditions. Indeed, based on the discussion in chapter 2, the "otherwise survivable crash conditions" are expected to cover ranges of vertical impact velocities beyond $v_z=30$ ft/s.

A crashworthy LH2 tank integration concept is considered that specifies tank mounts in terms of spokes and x-rods. The spokes are attached to the tank dome close to the tank poles. In total, 16 spokes are defined at the front respectively rear tank side, see Fig. 12. A distributed load introduction into the airframe structure is achieved by this design while the spokes converge to a concentrated hub at the tank pole enabling a tank installation that aligns with an isostatic support. Mass retention with regard to horizontal crash loads is ensured by x-rods that are installed at the tank cylinder and that provide load limiting function, e.g. by activation of progressive tensile failure in case of exceeding a given design threshold [58]. Spokes and x-rods are oriented tangentially to the tank shell minimizing any risk of tank penetrations by the tank mounts. Load attenuation function is provided by a sub-tank framework structure that consists of a curved crossbeam and framework struts. The struts are arranged in x-pattern to enable strut orientations tangentially to the tank to prevent risk of tank penetration. Hence, the struts are intended to fail under bending load rather than under axial crushing leading to reduced mass specific energy absorption as a cost to prevent tank penetrations. The entire lower airframe with curved crossbeam and framework struts is designed to prevent an unrolling crash kinematics and instead ensures the fuselage failure pattern is a flattening kinematic. Once the fuselage impacts the ground and lower framework crushing is initiated, the crush loads lead to minor bending deformation of the curved crossbeam closing the gap to the LH2 tank and providing contact for a direct load path of the tank inertia loads through the lower fuselage structure to the crash zone. For an assumed fuselage diameter of 5.3 m, the available crash

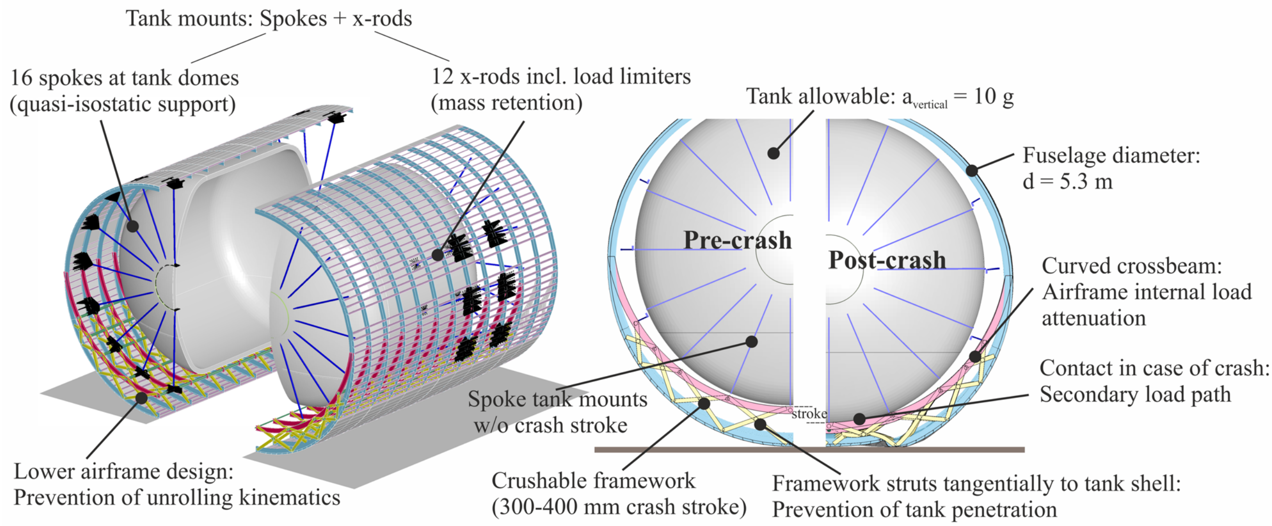

Fig. 12 Design example for crashworthy LH2 tank integration

stroke in the lower framework structure is in the range of 400 mm. With a selected tank allowable of 10 g as maximum vertical acceleration, vertical impact conditions of up to 35 ft/s (10.7 m/s) can be achieved, assuming ideal load attenuation at constant acceleration. In contrast, considering a triangular pulse as airframe crash response significantly reduces the vertical impact capacity, hence an efficient crush response of the lower framework structure is key.

According to the proposed building block presented in Fig. 4, the component, major, and full airplane level was applied in a first conceptual design study using explicit finite element (FE) simulation, as illustrated in Fig. 13. The FE model generation was performed using an automated in-house process chain based on the Common Parametric Aircraft Configuration Schema (CPACS) and the process chain PANDORA [59, 60]. Specific design input such as the tank mounts or the lower framework structure was separately added to the model.

Simulation results presented in the following are focused on the forward LH2 tank which provides a tank volume of 45 m^3 and features an outer tank diameter of 4.5 m with a structural tank mass of 4500 kg and a total tank mass of 7700 kg, including the LH2 tank contents. The airplane design as well as the airframe structure is generic and based on [61]. A metallic structure is assumed for airframe and tanks, mainly based on Aluminium 2024 respectively Aluminium 7075 material data. At this conceptual design level, simplified material data based on room temperature was considered for the tank structure and cryogenic condition effects for the inner tank material were neglected. At component level, the fuselage section model consisted of approximately 800,000 elements with mesh sizes ranging from 15 to 60 mm. At full-scale level, the full fuselage model contained approximately seven million elements with a mesh size range from 15 to 120 mm. Discretization mainly considered fully-integrated shell elements (elform 16) while beam elements (elform 6, discrete beam) were selected for modelling of structural details such as spokes and x-rods, as well as beam elements (elform 2) for reinforcement structures in the wing box or fuselage tail. Modelling best practices for crash analyses were applied, however, at the full-scale level the selected modelling methods for full fuselage analyses are under development and not yet fully validated. While this approach is reasonable for conceptual design applications, further full-scale analyses at the preliminary and detailed design level would require more mature validation of the full-scale modelling methods. The simulations were performed using the commercial FE software LS-DYNA (R13.1.0, single precision), running on a single node of a multi-node Linux workstation. Each node is equipped with two AMD EPYC 7313 16-core processors. Using a single node (two 16-core processors), the elapsed time for the component level simulations was six hours while the full-scale simulations required eight days on four nodes.

Simulation results of two exemplary load cases are presented in the following. First, the fuel tank integrity drop test is considered, according to load cases 'LC#11(x)' in Table 2. A robustness load case is selected with an assumed vertical impact velocity of $v_{z\_max\_local}$=30 ft/s (9.1 m/s) as well as a pitch angle of 5°. This load case is not explicitly listed in Table 2 but represents an interstage of the listed 'LC#11(x)' load cases with 3.5° and 7° pitch angle. The plot of global energies is presented in Fig. 14(a) and shows smooth energy absorption until 90 ms after first impact, as well as minor rebound indicating a small amount of elastic energy while the majority of kinetic energy is absorbed by material plasticity and damage. At conceptual design level,

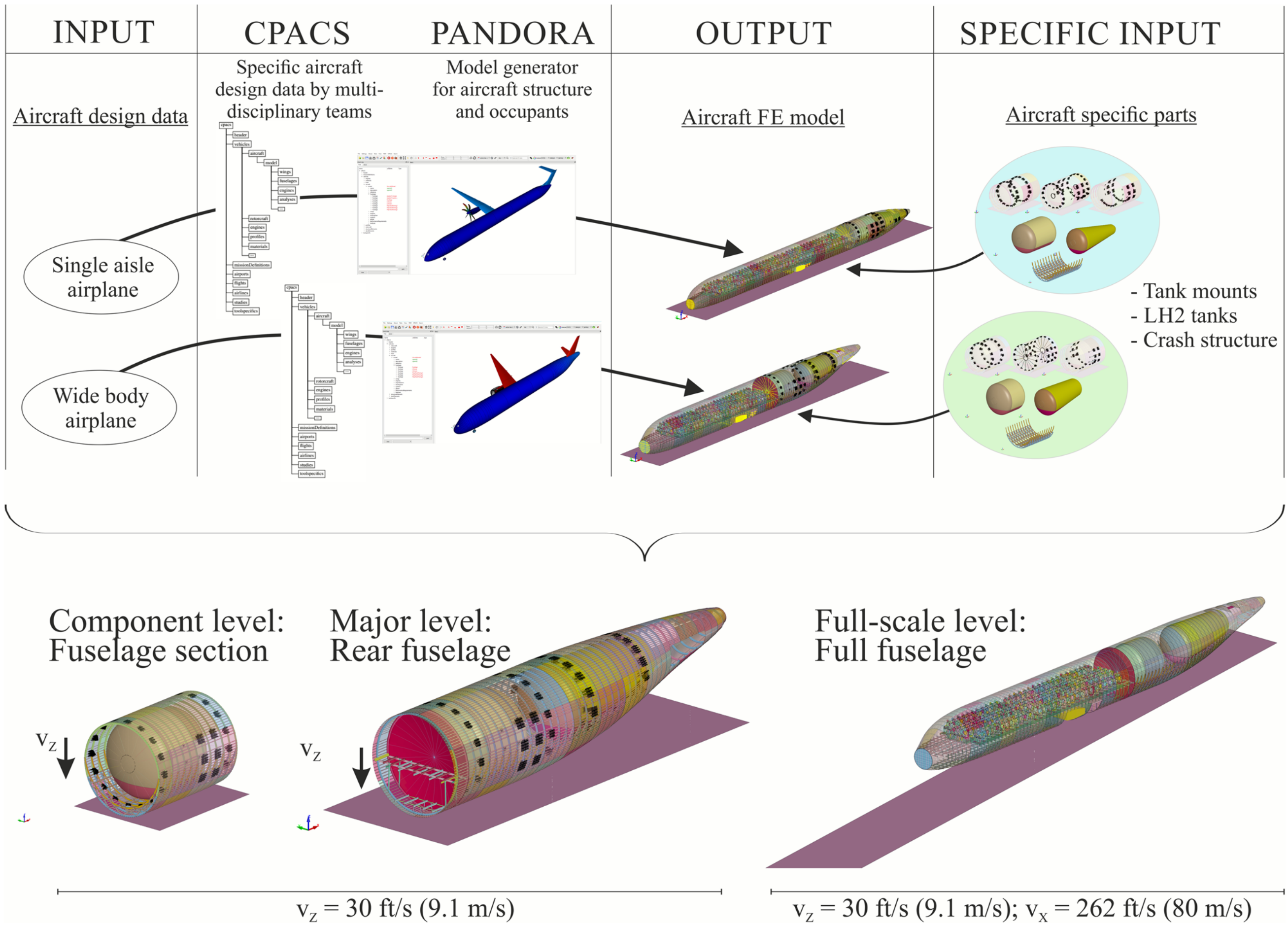

Fig. 13 Conceptual design models at component, major, and full airplane level

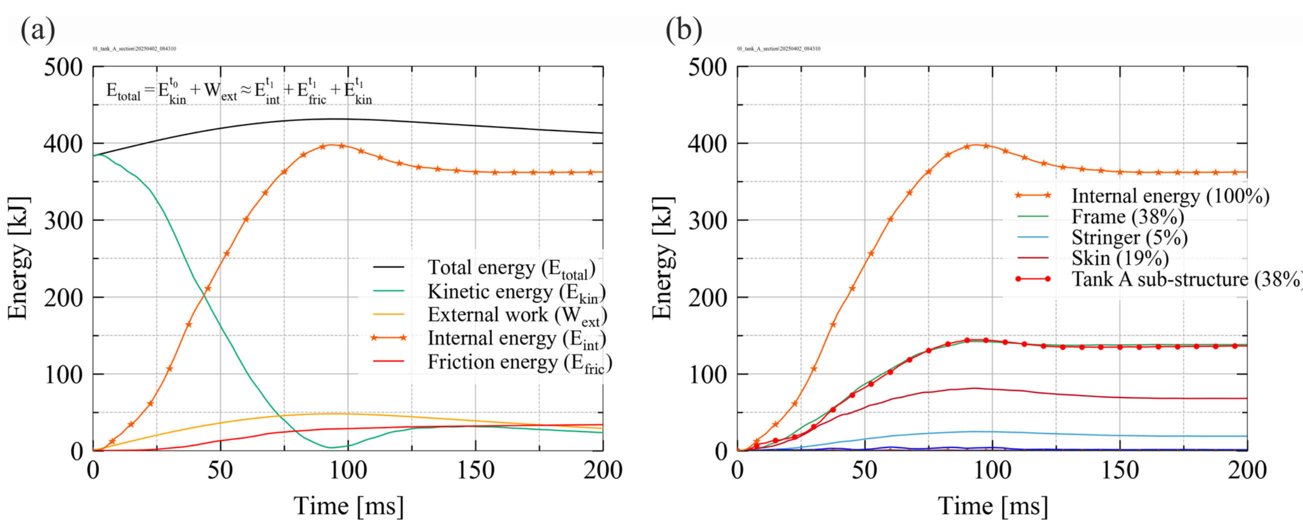

Fig. 14 Fuel tank integrity drop test with $v_{z\_max\_local}$ = 30 ft/s (9.1 m/s) and 5° pitch angle: **a** plot of global energies, **b** plot of internal energies

where efficient modelling strategies are used, this can be interpreted as indication for sufficient modelling quality to capture the main structural failure effects while preventing too stiff response caused by model simplifications.

The plot of internal energies, illustrated in Fig. 14(b), clarifies the structural contributions to the energy absorption. The frame structure as well as the lower framework structure each contributed with 38% to the total internal

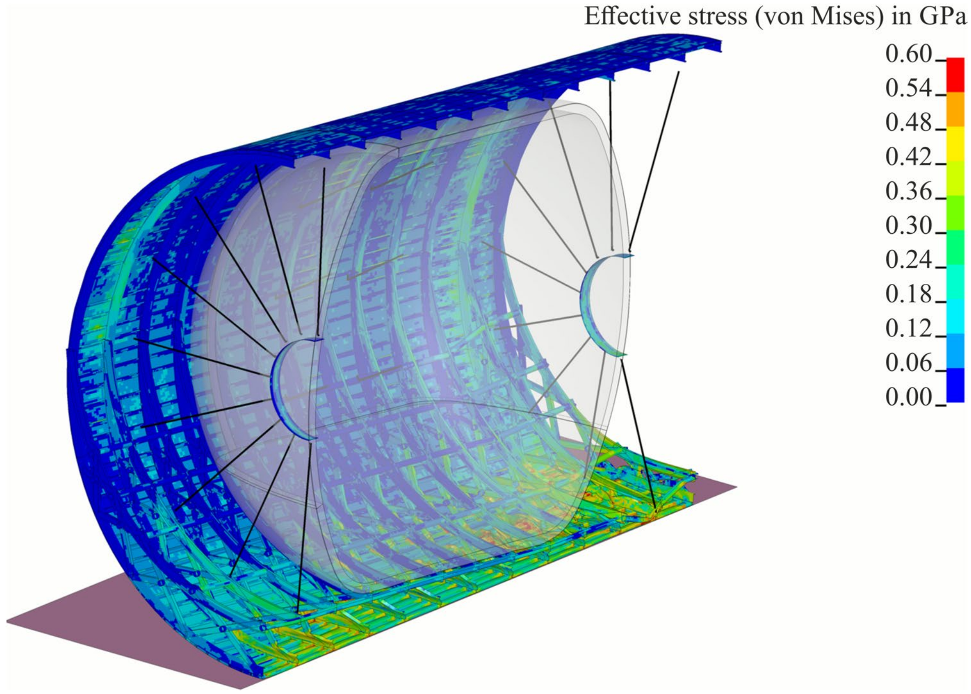

Fig. 15 Fuel tank integrity drop test with $v_{z\_max\_local} = 30$ ft/s (9.1 m/s) and 5° pitch angle: effective stress contour plot at maximum deformation

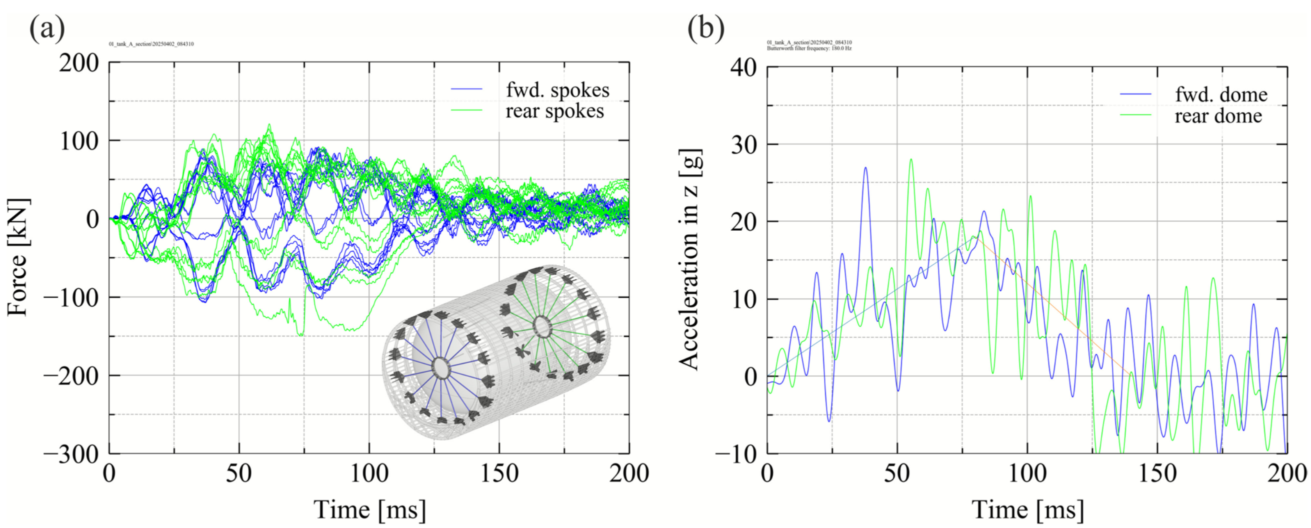

Fig. 16 Fuel tank integrity drop test with $v_{z\_max\_local} = 30$ ft/s (9.1 m/s) and 5° pitch angle: **a** axial forces in the spokes, **b** accelerations at tank domes with Butterworth filter frequency of 180 Hz

energy, followed by the skin structure with 19%. Comparably high energy absorption by the skin structure can be explained by the novel lower fuselage design and the resulting local crash kinematics of the sub-tank framework structure combined with a 5° pitch angle impact.

An effective stress contour plot at maximum deformation is presented in Fig. 15. Uniform crushing of the lower framework structure can be seen according to the pitch angle of 5°, while the contour plot indicates higher stresses in the sub-tank structure at the spoke regions where additional crash loads from the tank structure are introduced in the lower fuselage structure.

Axial forces in the spokes are plotted in Fig. 16(a) showing maximum compression forces in the range of 100 kN. With a spoke length of approx. 1700 mm, critical buckling loads for reasonable spoke cross-sections (tube with $d_{outer} = 150$ mm, $d_{inner} = 140$ mm) are significantly higher, hence there is minor risk for spoke buckling. The acceleration pulses measured at the forward and rear tank dome are depicted in Fig. 16(b). The pulse shape corresponds to a triangular pulse indicating potential for further design improvements of the lower framework structure to obtain an optimal constant acceleration. With the available crash stroke initially designed for a tank acceleration of constant

10 g, the true pulse shape as a deviation from optimum finally resulted in tank peak accelerations of 18 g, considering the triangular mean value pulse. As discussed in chapter 4, Fig. 6, this example shall highlight the importance to find the overall optimum in such a design process. Based on the given results, further design improvements should consider both, improvements in the airframe crash structure to obtain acceleration responses towards optimal, constant load levels, but also crashworthy design considerations for the tank structure itself to sustain higher peak accelerations beyond the assumed 10 g.

The second exemplary load case considers crash impact at full airplane level, according to load cases 'LC#10(x)' in Table 2. In this performed simulation a full fuselage model instead of a full airplane model was used. While fuselage masses and mass distributions (payload, structure, systems) are considered, other full airplane aspects like wing lift, or landing gear and engine installations are not considered in this specific simulation at conceptual design level. The simulation was performed with a vertical impact speed of $v_{z\_max}=30$ ft/s (9.1 m/s), a horizontal impact speed of $v_x=262$ ft/s (80 m/s), and a pitch angle of 5°. In this example, for comparison reasons, an identical vertical impact velocity is assumed for the airplane level analysis (v_{z_max}) compared to the previously discussed fuselage section level analysis ($v_{z\_max\_local}$). As for the previous simulation, a friction coefficient of $\mu=0.3$ was specified for all contact interactions, assuming moderate friction and hence, as a conservative approach, preventing too large portions of energy dissipation by frictional effects. With regard to the vertical impact velocity and the airplane attitude, the same crash conditions are considered for both exemplarily presented load cases.

An effective stress contour plot at maximum deformation is presented in Fig. 17 with focus on the rear fuselage. The axial forces in the spokes are plotted in Fig. 18 together with the spoke forces obtained for the fuselage section analysis. The comparison of presented simulation results for both load cases reveals higher structural deformation at full fuselage level with utilization of the entire available crash stroke in the sub-tank framework structure. In Fig. 18, the single curve showing a force spike of approx. -270 kN indicates hard impact of the rear lower center spoke after full crushing of the sub-tank structure. Hence, the crash design capacity is exceeded.

The different results between fuselage section and full fuselage level can be explained by the entire fuselage inertia not considered at fuselage section level. With positive pitch angle, first impact of the full fuselage occurs at the rear. In this initial crash phase, the entire fuselage mass inertia as well as the rotational inertia acts at the local crash zone at the rear fuselage. In the subsequent crash phase, the crash pulse introduced at the rear fuselage leads to pitch rotation and further crushing of the forward fuselage zones. The example highlights that effects identified at fuselage section level do not necessarily fully represent the true crash conditions at tank installation sections. In this example, the combination of a caudal tank configuration with non-zero pitch angle attitude at impact lead to the obtained differences in both presented analyses.

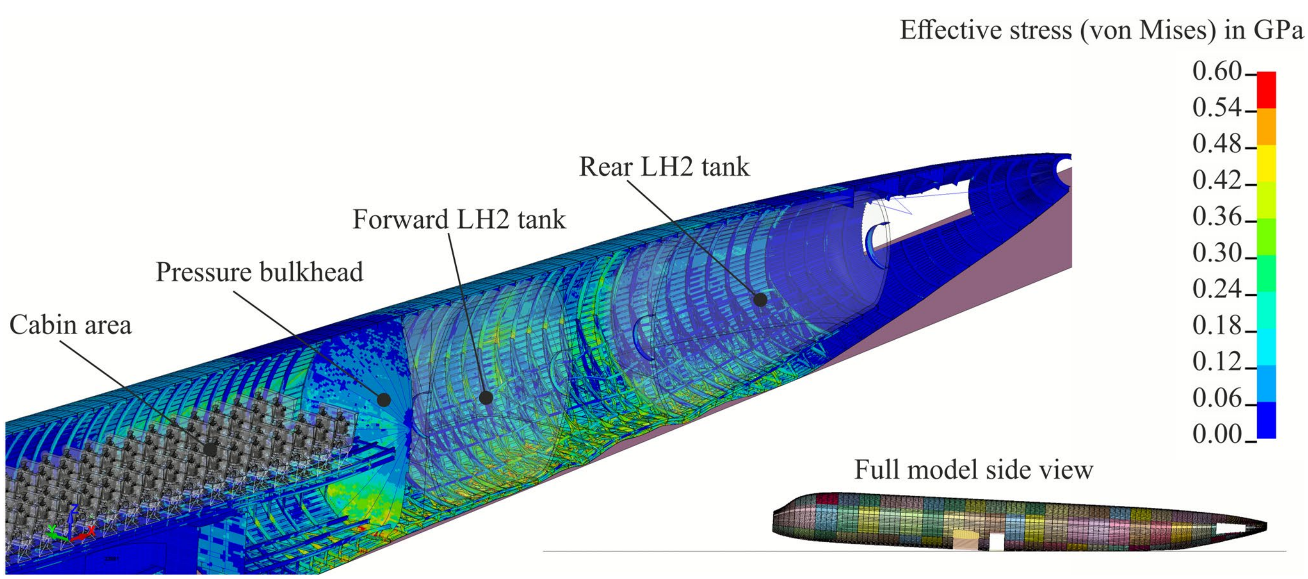

Fig. 17 Crash impact at airplane level with $v_{z\_max}=30$ ft/s (9.1 m/s) and 5° pitch angle: effective stress contour plot at maximum deformation (t = 110 ms)

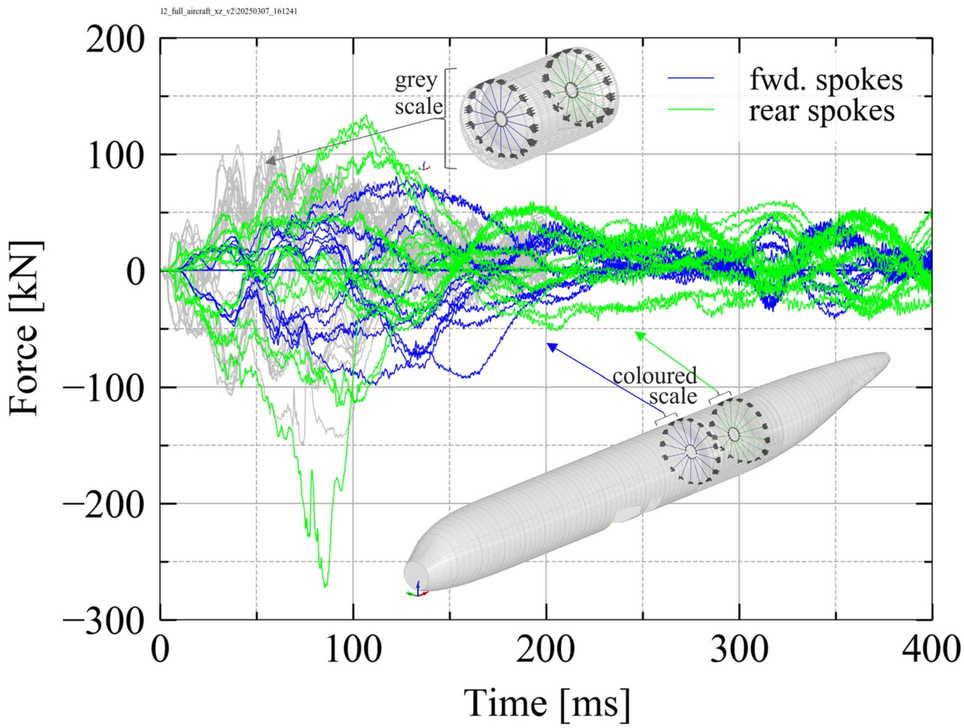

Fig. 18 Crash impact at airplane level with v_{z_max} = 30 ft/s (9.1 m/s) and 5° pitch angle: axial forces in the spokes. For comparison reasons, axial spoke forces of the fuselage section simulation are additionally plotted in grey scale

7 Summary and conclusion

This paper presents results of initial research on crashworthy LH2 tank integration in transport airplanes, with the intent to provide aspects that may be used in further research work. Crashworthiness requirements and load cases were defined, and a proposal for a crashworthiness demonstration strategy was developed. Aim of this first part of the paper is to provide a potential framework of requirements, load cases, and demonstration path that may be applied, or further developed, in future research studies.

In a second part of this paper, design aspects for a crashworthy LH2 tank integration are presented and discussed on a theoretical basis. A 2-layer safety approach is proposed that considers the LH2 tank not only as a system item to be installed in a crash safe designed airframe but instead proposes additional crash safety features for the LH2 tank itself. This second layer of crash safety shall prevent hazardous tank leakage under more severe crash conditions when the airframe crashworthiness capacity is exceeded. As a main conclusion, optimal crash safety as well as overall lightweight design is expected for design solutions that consider robust crash features also for the LH2 tank. Outcomes from past research work on CRFS can build a valuable basis for future research work on crashworthy LH2 tank structures.

Finally, an exemplary application at conceptual design level is presented in a last part of this paper. A design example for crashworthy LH2 tank integration is discussed and exemplary simulation results of selected load cases at the fuselage section and full fuselage level are presented. At the full fuselage level, effects were identified in the simulation that were not captured in the fuselage section analysis. This outcome confirms the general approach presented for the crashworthiness demonstration strategy that proposes the consideration of large structural scales beyond the major (fuselage section) level to capture relevant effects which otherwise are not identified.

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Data availability The raw/processed data required to reproduce these findings cannot be shared at this time as the data also forms part of an ongoing study.

Declarations

Competing interests The authors declare no competing interests.

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