Crashworthy design and energy absorption mechanisms for helicopter structures: a systematic literature review

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Abstract

Helicopters are versatile aircraft that can engage numerous maneuvers, which have been extensively used in military and civil industries such as performing ground surveillance, rescue missions, air ambulance and fire-fighting. However, helicopter crashes sometimes occur owing to technical failures or human errors. Accordingly, the crashworthy design of helicopters has always remained a top priority to prevent catastrophic structural failure and significant casualties. The crashworthy performance of helicopters can be immensely improved with well-designed energy absorption materials or structures. This paper presents a systematic literature review on crashworthy design and energy absorption mechanisms for helicopter structures. Firstly, the historical development of aircraft crashworthiness investigation at various periods over the past few decades is presented. Then, some typical energy absorbing components such as rings, tubes, honeycombs, corrugated structures and emerging energy absorbers are introduced to act as the major structural elements for the crashworthy design of helicopters. After that, an emphasis is placed on the dynamic behavior and energy absorption of typical helicopter structures such as the landing gear, subfloor, full-scale airframe, helicopter crashworthy seats, fuel tank and helicopter blade. In addition, representative helicopter crash scenarios such as bird strike, water impact and the impact response and injury of the occupants are described. Finally, the crashworthy evaluation criteria of helicopter structures are summarized in

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this paper. This article is intended as a high-level literature review of crashworthy design and impact protection of helicopter structures.

Keywords: helicopter, crashworthiness, structural impact, crash dynamic.

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1. Introduction

Helicopters are a type of aircraft that provide lift force, propulsion and control depending on rotating wings. The engine of a helicopter drives the rotor system, leading to high-speed rotation of the blades. The helicopter blades spin along the yaw axis with a high angular velocity, generating an aerodynamic force by the relative movement of a blade surface and air [1]. Compared with fixed-wing aircraft, an aerodynamic force can still be obtained by the rotating blades of a helicopter under the condition of zero translation velocity. Thus, helicopters have the capability of translational flight, hover flight, and vertical take-off and landing, making it one of the most versatile types of all the aircraft. The history of helicopter development started with the mention of the Chinese top in 400 B.C and Leonardo da Vinci's work in the late 15th century. Many some new attempts with regard to the helicopters were tried in the last half of the 19th century. Greater progress in the helicopter development was made during and after World War Ⅰ, which overcame the difficulty of an insufficient power source [2].

So far, helicopters have been extensively used in numerous military and civilian applications. However, helicopter safety issues have drawn more and more attentions in recent decades due to the fact that a number of helicopter accidents have occurred owing to structural failure or human errors [3]. For example, there were 211 accidents that occurred from 2006 to 2015 in Brazil with an average of 133 deaths per year and 63 deaths per hundred accidents [4]. Helicopters have a 17.3 times risk of fatal accidents than the passenger cars [5]. In order to guarantee flight safety, helicopters are traditionally designed according to the requirements such as static strength, fatigue strength, aerodynamics, stability and control capability. However, serious damage to the major structural components and severe injury to the occupants may occur in the event of a helicopter crash. The impact force caused by the crushing of helicopter structures can exert directly on the passengers and the crucial escape routes. The excessive impact energy exceeds the human tolerance, leading to heavy casualties for the occupants during a helicopter crash. However, compared with fixed-wing aircraft, it is more difficult to escape safely from a helicopter crash by an effective ejection lifesaving system due to the fact that helicopters usually fly missions at low altitude or nap-of-the-earth mode, there is little time to perform an ejection sequence in the event of a crash. In addition, there is a significant risk that the pilot may collide with the rotary wing if adopting an ejection lifesaving system. Accordingly, the unique solution to protect the occupants from a helicopter crash depends on the crashworthy design of helicopter structures.

According to the helicopter crash accident analysis, injury to the occupants during a helicopter crash comes principally from three aspects: (a) the inertial overload imposed on the occupants by sudden acceleration; (b) the contact injury resulted from the collision between the occupants and hard surfaces in the cabin; (c) the environmental injury such as the fire caused by fuel leakage, the asphyxiation caused by smoke and fume and the drowning caused by water. Fortunately, based on the helicopter accident survey, 90% of these accidents have survival conditions for the occupants [6]. Thus, the crashworthiness design has become increasingly important during the development of helicopters. Aircraft crashworthiness is generally defined as the capability of an aircraft system to protect the occupants from the fatal or serious injury in the event of an accidental crash. There involves two significant topics for the aircraft crashworthy design, namely impact mitigation or energy absorbing structure and human tolerance. The former can dissipate the impact kinetic energy through the aircraft seat, airframe, subfloor and landing gear in a controllable way, which has the capability of reducing the shock overload transferred to the occupants and maintaining the structural integrity of an aircraft when a crash occurs. The airframe should survive with minimal deformation so as to provide the occupants with a necessary livable volume. The latter specifies the limit of external force/impulse transferred to the passengers within the human body's tolerance, which has a great influence on the design of energy absorbing structures. Thus, the main purpose of aircraft crashworthy design is to design the optimum energy absorbers to minimize the occupant injury and maximize the survival rate. Generally, the larger the energy absorbed by the helicopter structure during an accidental crash, the lower injury or death to the occupants. In accordance with the above principles, the critical factors in the structural design include: (a) The impact load imposed on the occupants should keep within the human tolerance; (b) Protecting the occupants from the injury caused by the secondary impact; (c) Preventing the fire caused by fuel leakage in the event of crash; (d) Ensure the effective emergency evacuation passage. Taking these factors into account, the step-by-step energy absorption method can be adopted in the helicopter conceptual design stage. The energy absorption system is composed of the helicopter landing gear, fuselage and other sub-systems, dissipating the impact kinetic energy in a step-by-step manner.

In response to the present lack of overview papers on the crashworthy design of helicopters, this paper is specifically intended for the researchers in the field of aircraft crashworthiness design to use for reference, which is focused on crashworthy design and energy absorbing mechanisms of helicopter structures. Section 2 briefly presents the historical development of aircraft crashworthiness design around the world. Section 3 describes typical energy absorbing structures such as rings, tubes, honeycombs, corrugated beams/plates and emerging energy absorbers, which are generally used as main energy absorbers in helicopter structures to protect the passengers from injury. Section 4 reviews the dynamic behavior and crashworthy design of the landing gear, subfloor, full-scale airframe, helicopter crashworthy seat, fuel tank and helicopter blade. The representative helicopter crash scenarios such as bird strike, water impact and the response and injury of the occupants are introduced in Section 5. Finally, the crashworthiness design and evaluation criteria of helicopter structures are concluded in Section 6.

2. Historical development of aircraft crashworthiness

The concept of protecting the occupants from injury in the event of an accidental crash is practically as old as the powered aircraft itself. Fig. 1 shows the historical development of aircraft crashworthiness design. After the first few aircraft crashes happened, leather jackets and helmets were in tremendous demand to prevent serious abrasions and provide head protection. The earliest research work on the aircraft crashworthiness dates back to Hugh DeHaven's pioneering work in the 1940s. Owing to the survival from a midair collision which took three lives during the crash, DeHaven launched a research plan on crashworthiness under the support of the Crash Injury Research. According to the survey, a majority of crash accidents, the occupant injury resulted from shock loading that could be alleviated by using crash energy absorbers. Specially, the earliest crashworthiness design criterion was proposed during the research [7]. Since the late 1950s, the U.S. Army initiated crashworthiness research based on data analysis of aircraft crash accidents and injuries. Under their efforts, the Army's crash survival design guide was finally published in 1967, which was a major milestone for aircraft crashworthiness design [8]. Afterwards, the Army flight safety and helicopter crash testing program also validated the crashworthiness requirements described in the design guide. The subsequent anti-crash structures were generally designed according to the guide. It was shown that aircraft crashworthiness has been greatly eliminated and helicopter crash fires has been avoided in case of crash accidents.

Another important work in the development of aircraft crashworthiness design was the crash/fire experiments for several full-scale aircrafts, which were firstly carried out by the National Advisory Committee for Aeronautic Lewis Research Center in 1952 with a focus on the post-crash aircraft fires initiation mechanism [9]. Subsequently, the Aviation Safety Engineering and Research (ASER) performed a crash test program using two TC-45J twin-engine airplanes during 1964-1965 for the U.S. Army [10]. Since then, two full-scale crash tests of a Lockheed L-1649 and a Douglas DC-7 were conducted by the Federal Aviation Administration (FAA) at the flight safety foundation facility in Phoenix in 1964. The crash environmental data, fuel containment and behaviors of the aircraft sub-structures were measured from these tests [11, 12]. In 1972, the National Aeronautics and Space Administration (NASA) initiated a cooperative research plan with FAA to improve the crashworthiness of the general aviation aircraft. The research plan mainly focused on the development of analytical and experimental method for the crash dynamics of aircraft [13]. In order to simulate a survivable crash landing, FAA conducted a full-scale transport crash test in which a remotely piloted B-720 impacted with the ground in the early 1980s.

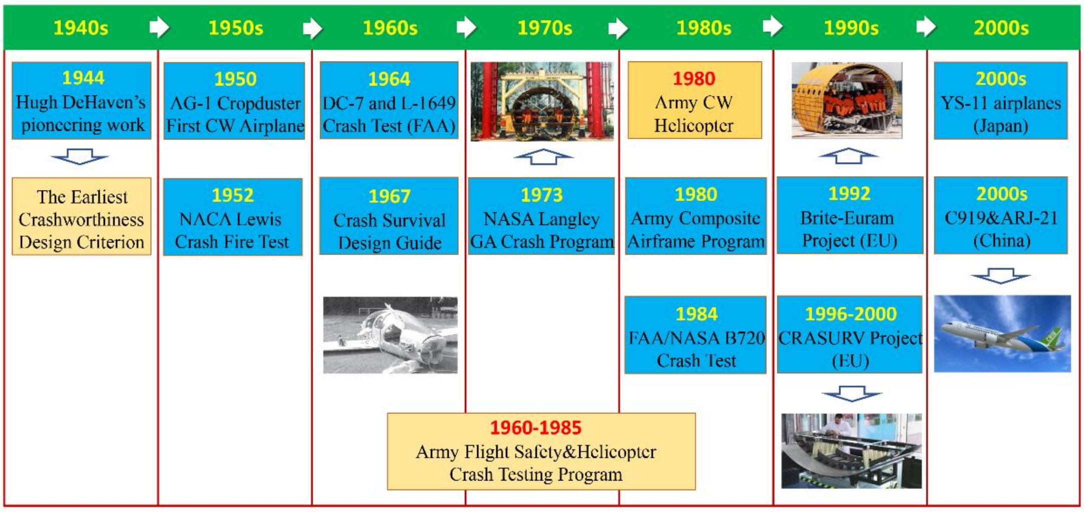


Fig.1. Historical development of aircraft crashworthiness design.

In 1970, some European countries jointly established Airbus aimed to design and manufacture aircraft, and Airbus initiated development of the research plane on civil airplane crashworthiness in 1990s. Especially, the European Aeronautic Defence&Space (EADS), the German Aerospace Center (DLR), Netherlands Aerospace Centre (NLR) and other related research institutes conducted a systematic research on aircraft crashworthiness under the support of the third to fifth European Union (EU) framework plan. For example, the traditional metal fuselage structural crashworthiness was studied under the support of Brite-Euram Project [14]. From 1996 to 2000, the mechanical property and failure mechanism of carbon fiber reinforced composites, development of impact analysis code, structural design and experimental validation of composite energy absorbers were studied under the support of the CRASURV Project [15]. In the early 21st century, the CAST Project supported the dynamic response analysis of aircraft structures under high-velocity impact loading and the research on water landing analysis code of helicopters [16].

In recent years, Japan Aerospace Exploration Agency (JAXA) has also been engaged in research on civil aircraft crashworthiness. A systematic investigation based on YS-11 airplanes was conducted to evaluate the energy absorption elements, simplified cabin subfloor structures and full-scale aircraft structures [17, 18]. At the beginning of the 2000s, a research plan for the development of the large civil airplane such as C919 and ARJ-21 was established in China, and a majority of research were conducted on the crashworthy design of civil airplanes. The corresponding research involves the design and analysis of energy absorbers, finite element modelling techniques of the fuselage structures and cabin interiors, crash tests of the full-scale airplanes and the crashworthy evaluation methods [19-21].

Although aircraft crashworthiness was put forward very early to guide aircraft design, it had not attracted sufficient attention until the outbreak of the Vietnam war. Then, aircraft crashworthiness was regarded as one of the key issues, which was equally important as that of weight, load factor and fatigue life in the primary design stage for the U.S attack helicopters. The first helicopters that gave priority to crashworthiness design were U.S Army UH-60 Black Hawk and AH-64 Apache helicopters. Up to that time, aircraft crashworthiness approaches have been widely used in the structural design of helicopters by numerous aircraft manufacturers. For example, Italian helicopter A129 has the crashworthy seat, tail dragger landing gear and exchangeable self-sealing crashworthy fuel tank. The cockpit of “dolphin”, a helicopter made in France, has the ability to withstand over loading as high as 15g (g means the gravitational constant). Besides, the fuselage of “tiger”, a helicopter made in France and Germany, is capable of withstanding a maximum vertically impact velocity of 10.5 m/s, and the landing gear will not collapse until the vertical crash velocity reaches 6.5 m/s [22].

3. Typical energy absorption structures

3.1 Ring

Metallic thin-walled rings have been widely used as energy absorbers owing to the high energy absorption capacity and stable failure mode [23-26]. In comparison with the axially loaded thin-walled tubes, the force-displacement curves of the thin-walled rings is smoother. As described in Fig. 2, there are two typical large plastic deformation modes for the metallic thin-walled rings under the compression loading, namely a four-hinge deformation mode proposed by DeRuntz and Hodge [27], and a six-hinge deformation mode proposed by Burton and Craig [28]. However, the identical force-deflection curves were found due to the fact that the force analysis diagrams in the undeformed sections were the same for the two typical plastic deformation modes. Furthermore, Redwood [29] investigated the influence of strain hardening effects on the mechanical response of the lateral loaded rings, which was not taken into account in DeRuntz and Hodge's work. Reid and Reddy [30] established an more accurate model by using an arc to replace the concentrated hinge, and the discrepancy between the theories and experiments was finally solved. Besides, elliptical rings have particular advantages over the circular rings in terms of energy absorption owing to the different semi-axes. A systematic theoretical model was also proposed for the elliptical rings under quasi-static and impact loading [31, 32].

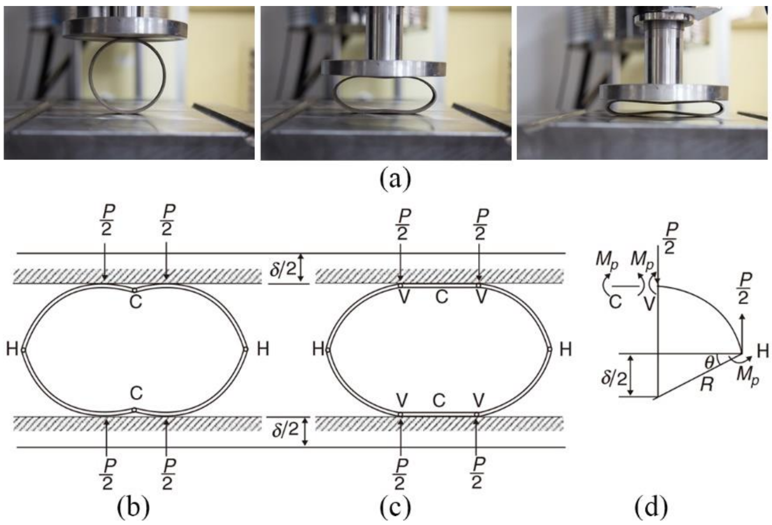


Fig. 2. Collapse mechanisms of circular rings: (a) Deformation process of a ring; (b) DeRuntz and Hodge' model [27]; (c) Burton and Craig's model [28]; (d) Forces imposed on the deformed segment.

The energy absorption capacity of thin-walled rings is mainly dependent on the plastic bending around the plastic hinges. Plastic strain localization occurs during the plastic bending failure mode, leading to an inefficient energy dissipation performance [33]. In order to overcome the drawback and maximize the energy absorption, plastic deformation should appear for a large volume of material. The solution to this issue is constraining the lateral deformation so as to generate more plastic hinges and dissipate more impact energy. Several types of constrains such as a grooved block and a V-shaped block (Fig. 3a and 3b) were introduced to enhance energy absorption capacity [34]. Another alternative solution is adopting foam-filled thin-walled rings (Fig. 3c) to constrain the lateral deformation, and using filler materials between the two thin-walled rings can improve the energy absorption capability [35-37]. Besides, the nested lateral ring/tube systems have been considered as an efficient energy absorbing device especially in a situation where limited design space is available such as the helicopter cabin [38-40]. For example, Olabi et al. [41, 42] studied the impact mechanical response of the nested tubes (Fig. 3e) under the laterally dynamic crushing loading. Yang et al. [43] proposed a circular-elliptical nested ring system (Fig. 3f) which has a more stable plateau force compared with the other ring system. A.Baroutaji et al. [33] investigated the mechanical properties of nested tube systems with three different configurations (Fig. 3d). Furthermore, the circular ring systems are generally arranged as a one-dimensional chain to mitigate the impact load [44, 45].

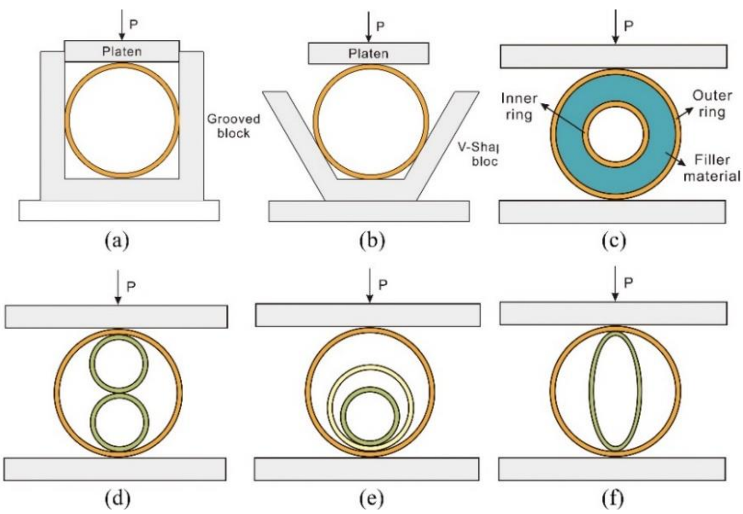


Fig. 3. Rings systems: (a) Grooved block [34]; (b) V-shaped block; (c) Foam-filled sandwich rings [35-37]; (d) Externally tangent nested rings [33]; (e) Internally tangent nested rings [41-42]; (f) Circular-elliptical nested rings [43].

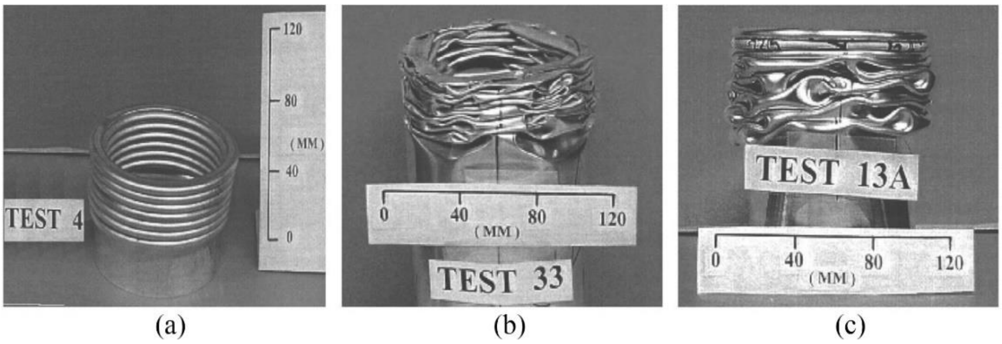


Fig. 4. Deformation modes of axially loaded tubes:

(a) ring mode; (b) diamond mode; (c) mixed mode [48].

3.2 Tube

In the field of energy absorption, tubes have drawn much attentions owing to the stable crushing load and long stroke. The energy absorption performance and failure mechanism of different tubes under the axial loading have been widely investigated in numerous literatures [46, 47]. A majority of experimental tests of circular aluminum tubes under axial compression load indicated that three types of deformation modes were presented, namely ring mode, diamond mode and mixed mode as depicted in Fig. 4. The deformation mode was mainly determined by the geometric configuration such as the ratio of length to thickness and the ratio of diameter to thickness [48]. The dynamic crushing response of circular tubes was also investigated by many researchers, these efforts mainly focused on the deformation mode transition from progressive buckling to dynamic buckling and the effect of impact velocity and material properties on the dynamic buckling behaviors [49, 50]. Besides, the energy absorption capacity of square tubes was slightly worse than that of circular tubes. Similarly, the deformation mode of square tubes could be classified into the extensional mode, inextensional mode, asymmetric mixed mode and non-compact crushing mode [51]. The triangular tubes were also studied in literature [52-54], however, the energy absorption capacity of the triangular tubes was the worst of all the tubes owing to the minimum corners [55]. Furthermore, some other novel tubes were proposed to improved mechanical properties. For example, the energy absorption capacity of thin-walled tubes could be greatly enhanced by filling the tubes with foam materials, which was attributed to the interaction between the tubes and foam materials [56-58]. Besides, Chen et al. [59, 60] designed the dumbbell-shaped tubes (Fig. 5a) that could interlock each other without providing any other lateral constraints under the impact loadings. Yang et al. [61] proposed a dimpled tube (Fig. 5b) which could reduce the initial peak load and the fluctuation of the crushing force.

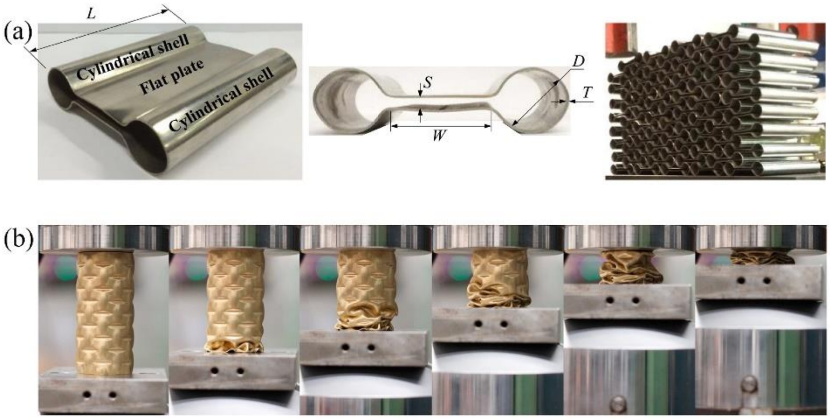


Fig. 5. Typical novel tubes: (a) Dumbbell-shaped tube [59]; (b) Dimpled tube [61].

In addition to tubes' folding behaviors, the other failure modes such as tube inversion, expansion, splitting, and tearing are also significant energy absorption approaches which can be used in numerous engineering structures to dissipate the impact kinetic energy in the event of a collision. Circular metal tubes are prone to invert internally or externally by embedding in a suitable fixture or using a specially designated die under the axial compression loadings [62]. As shown in Fig. 6, the deformed part of the circular tubes turns into a co-axial cylinder shell insider or outside the undeformed part of the circular tubes [63-65]. Investigation results indicate that a stable crushing force and a long stroke can be achieved during the inverting process. Generally, the stable crushing force and long stroke are regarded as good indicators for an energy absorbing structure. Tube expansion is a similar energy absorption method that a conical die is compressed into an expandable tube by applying an axial compression loading [66-68]. During the expansion process, the impact kinetic energy can be dissipated by plastic bending, plastic stretching and friction between the tube and the conical die. Furthermore, the plastic strain in a tube expansion is lower than that in a tube inversion during a compression. Thus, less ductile materials can be used in the design of tube expansion devices. Besides, tube splitting is also an efficient energy absorbing approach to dissipate the impact kinetic energy by bending, stretching and tearing failure modes. In order to achieve the splitting process, the tubes should be processed with a primary sawcut to guide the generation and evolution of the axial fractures [69, 70].

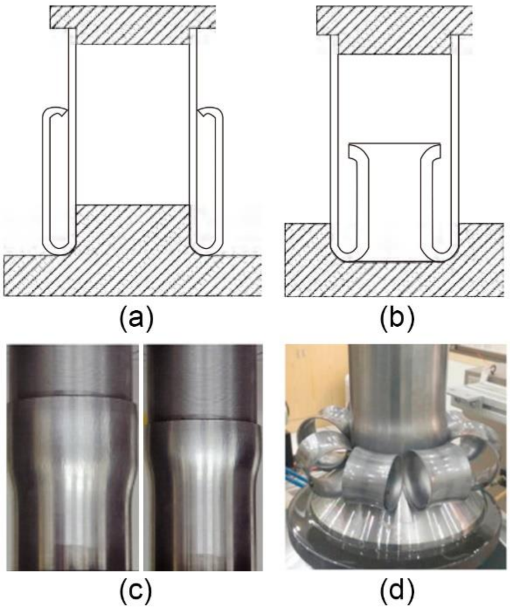


Fig. 6. Tubular energy absorbers: (a) Internally tube inversion [63]; (b) Externally tube inversion; (c) Tube expansion [66]; (d) Tube splitting [69].

Nowadays, composite materials have been extensively used as key structural elements in a majority of aerospace structures. The failure process of a composite tube also plays an important role in the energy absorption during a helicopter crash. When subjected to the impact loading, energy absorption can occur the matrix cracking, fiber failure or delamination to dissipate the impact kinetic energy as shown in Fig. 7a.

Thus, the composite tube may collapse with splaying progressive mode, progressive brittle failure mode, local buckling failure mode [71, 72]. Numerous investigations have been carried out to study the crushing behavior and energy absorption mechanism of composite tubes. For example, Hu et al. [73] analyzed the failure mechanism and energy absorbing performance of three kinds of hybrid composite tubes by both axial quasi-static and impact crushing tests. It was found that the peak load was greatly affected by the fiber content and fiber type. Although composite tubes consisting of one kind of brittle fiber have lower peak load than those with two kinds of fibers, it can improve the energy absorbing performance by adding hybrid brittle fibers into the composite tubes. Furthermore, composite tubes can dissipate more kinetic energy if failing with a progressive brittle failure mode. In order to achieve the purpose of improving energy absorption capacity, some novel composite tubes have also been developed over the past decades. Hussein et al. [74, 75] proposed a specially designed platen with cutting blades (Fig. 7b) to cut and crush composite tubes. It was proved that the composite tubes have lower initial peak force, higher mean crushing force and energy absorption capacity. Sun et al. [76] investigated the crushing behavior of the aluminum/carbon fiber reinforced plastics (CFRP) hybrid tubes. The hybrid tube can absorb more kinetic energy than the individual tubes owing to the positive interaction between the CFRP tube and the aluminum tube. Tong et al. [77, 78] developed an innovative chamfer external trigger (Fig. 7c) to make the composite materials fully crushed in the event of a crash. Besides, Heimbs [79] developed a new crash absorber by cutting the composite tubes into stripes and crushing the composite under bending (Fig. 7d), and it can be installed in a commercial aircraft to improve the energy absorption capacity.

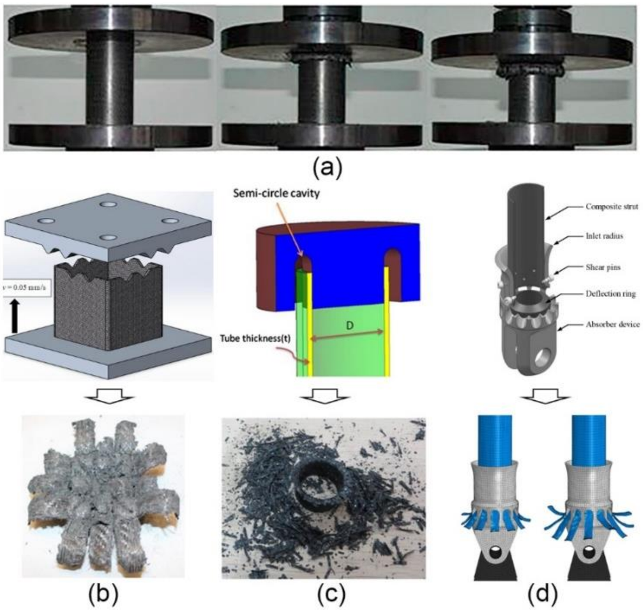


Fig. 7. Composite tube energy absorption devices: (a) Crushing process of composite tubes; (b) A specially designed platen with cutting blades [74, 75]; (c) A chamfer external trigger [77, 78]; (d) A crash absorber integrated in composite structures [79].

3.3 Honeycomb

Honeycomb structures have been widely used in a majority of engineering fields owing to the high strength-to-weight ratio, stiffness-to-weight ratio and prominent energy absorption performance [80]. The first artificial honeycomb was fabricated with the raw material of paper about 2000 years ago in China, and the modern manufacture technology of honeycomb structures appeared in the late 1930s. Some other honeycombs with different shapes have also emerged to strengthen the mechanical behaviors. So far, hexagonal honeycombs as shown in Fig. 8 have been the mostly used structures among all the honeycombs, and it can be manufactured by different methods and raw materials. Over the past few decades, the shape of honeycomb structures have evolved from hexagonal to triangular [81], square [82], circular [83], kagome [84] or other shapes (Fig. 9a) depending on different application requirements. Crashworthiness investigations have proved that honeycomb structures can be regarded as a good energy absorber to dissipate impact kinetic energy.

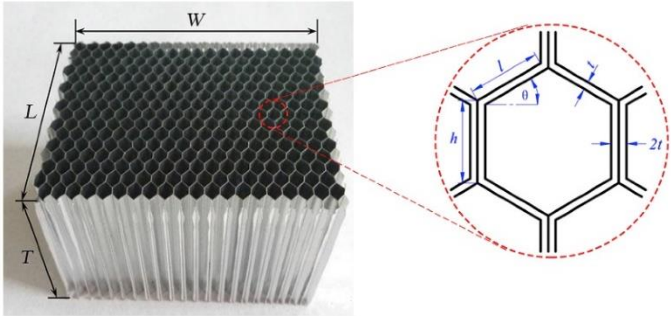


Fig. 8. Hexagonal honeycomb.

Until now, a number of novel honeycomb structures are developed to improve the energy absorption capacity. One of the most effective approach is to design the cross-section of honeycomb structures. For example, as shown in Fig. 9b, Yang et al. [85] developed a number of bio-inspired aluminum honeycombs by embedding horseshoe-shaped mesostructures into the traditional honeycombs. The energy absorption capacity and crushing force efficiency are greatly enhanced for horseshoe-shaped honeycombs. He et al. [86] studied the out-of-plane crashworthiness characteristics of spider-web honeycombs, the new type of honeycomb was constructed by adding coaxial hexagons into the original hexagonal unit-cells and connecting to the vertex by straight walls. Xiang and Du [87] proposed a bionic honeycomb by filling the unit cells with a special pattern according to the mesostructure of the ladybeetle. The results show that the bionic honeycomb has a better crashworthiness performance than the regular honeycombs. Yang et al. [88] designed a new circular-celled honeycomb structure by incorporating the petal-shaped mesostructures into regular honeycombs. The energy absorption of the novel honeycomb can be enhanced by up to nearly twice when compared to the regular circular honeycomb. Zhang et al. [89] proposed a new type of quadri-arc multi-cell honeycomb to pursue higher energy absorption capacity and crashworthiness properties. Besides, hierarchical structures have been extensively present in nature owing to the prominent mechanical behavior and weight efficiency, and the hierarchical micro-structures are also introduced into traditional honeycombs to improve its mechanical properties and crashworthiness performances. As shown in Fig. 9c, the hierarchical honeycombs are generally classified into two types: the first type is constructed by replacing all the vertexes of a traditional honeycomb with a smaller unit-cell and adopting the same approach to obtain the higher order hierarchical honeycomb [90-92]. For example, Sun et al. [93] studied the out-of-plane crashworthiness behavior of the first-order and second-order vertex based hierarchical honeycomb. It was proved that specific energy absorptions of the first-order and the second-order honeycomb could be improved by about 81.3% and 185.7% while the peak forces did not increase too much. Zhang et al. [94] investigated the crashworthiness of the bio-inspired self-similar regular hierarchical honeycomb under out-of-plane impact loading. The hierarchical cell organization can strengthen the material/strength distribution, leading to improved crushing strength and energy absorption capacity; The second type is designed by replacing every regular honeycomb's cell-wall by an entire honeycomb structure to construct a new hierarchical honeycomb [95-97]. Yin et al. [98] investigated the in-plane impact behaviors of bio-inspired hierarchical honeycombs on the basis of hexagonal, triangular and Kagome unit-cells, and the hierarchical honeycomb with triangular topology has the best crashworthiness property during the three kinds of honeycombs. Qiao and Chen [99] presented the crushing response of a second order hierarchical honeycomb whose cell walls were constructed by an equilateral triangular honeycomb, and the collapse stress has been improved compared with the regular hexagonal and triangular honeycomb structures.

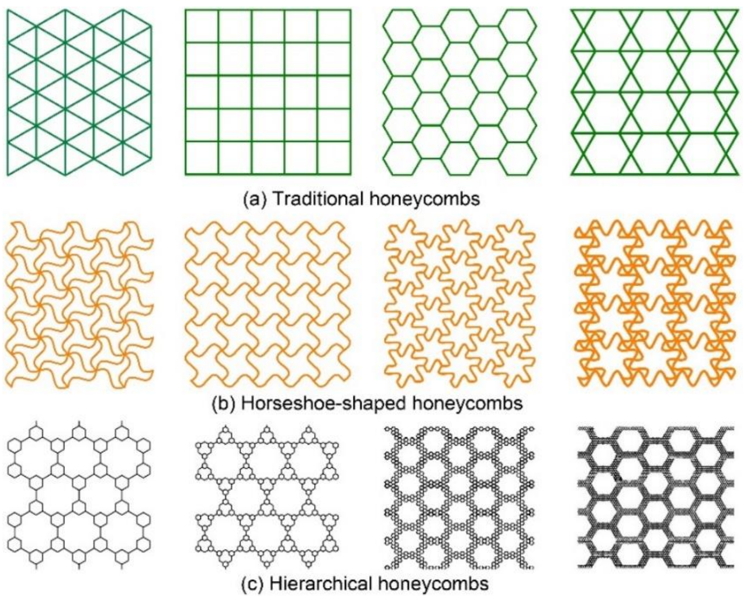


Fig. 9. Honeycomb structures with different cross-sections [85, 93, 99].

In addition, honeycomb structures with native Poisson's ratio have the unique mechanical characteristics due to the fact that it will shrink along the horizontal direction when compressed transversely. Thus, auxetic honeycomb have more advantages over the tradition honeycombs such as better indentation impedance, shear modulus, fracture resistance and energy absorption capacity [100-103]. Benefiting from this distinctive property, the auxetic honeycombs have found a great potential as protective engineering structures under the extreme environments including impact [104], blast [105] and ballistic loads [106]. Besides, honeycomb-filled structures are also widely used in the engineering field, which can greatly improve the mechanical property of the original structures. For example, honeycombs can be incorporated into the circular, square and composite tubes. The plateau force and energy absorption capacity of the tubes under the axial compression loading increase by filling the tubes with honeycomb structures [107-109]. Furthermore, honeycomb structures can be also filled into the corrugated sandwich structures, and the strength and energy absorption capacity exceed the sum of those of the individual components [110]. Besides, the mechanical properties and energy absorption performance can be also strengthened by adding fillers into the regular honeycombs such as foam materials [111] or tubes [112].

3.4. Corrugated structures

Corrugated structures have been widely used in the design of helicopter sub-floor structures, and a majority of research that proved that the corrugated shapes can provide stable and progressive crushing characteristics. For example, corrugated beams can absorb more energy owing to the higher buckling loading during crushing. Farley [113] conducted the quasi-static crushing experiments of honeycomb sandwich beams, sine-wave beams and two integrally stiffened beams. It was found that the energy absorption capacity of the sine-wave beam with appropriate geometry was better than that of other three types of beams. An empirical formula was proposed to predict the energy absorption capacity of composite sine-wave beams [114]. Mahe et al. [115] introduced corrugated composite beams into aircraft belly, and the deformation behavior of corrugated beams during a crash was studied based on finite element simulations. Hanagud et al. [116] studied the crushing performance of graphite epoxy composite sine-wave webs subjected to axial compression loadings. The failure initiator was not always negligible or beneficial for the energy absorption capacity, the width of sine-wave webs was not the primary influence factor. Feraboli [117] demonstrated that corrugated plates with sinusoidal or semi-circular geometry were capable of self-stabilizing deformation and could be manufactured with minimal cost, and the large-amplitude sinusoidal or semicircular corrugated plates were more suitable for standardization than the small-amplitude sinusoidal corrugated plates. The above investigations on the crashworthiness performance of sine-wave corrugated webs were mainly dependent on experimental methods. However, numerical simulations of the crushing process for the corrugated plates could provide more details on the energy absorption mechanism. In order to bear on this problem, Sokolinsky et al. [118] established a finite element model of the corrugated plate made of carbon–epoxy fabric composite material to analyze the intralaminar and interlaminar failure mechanisms. The in-plane and delamination response were respectively simulated based on a proposed constitutive model and the cohesive surface capability in Abaqus. Jiang et al. [119] investigated the crushing and energy absorption performance of a composite sinusoidal plate subjected to quasi-static crushing load. Fig. 10a-c present the failure modes of composite sinusoidal plates, and the simulation results are in good agreement with the experimental results regarding to the failure mode, the mean crushing force and energy absorption capacity.

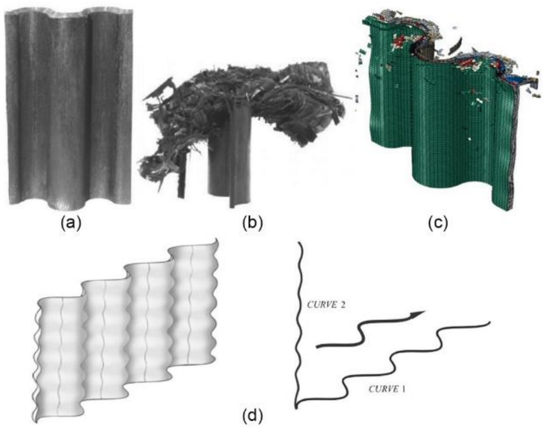


Fig. 10. Failure modes of composite sinusoidal plate: (a) Specimen; (b) Experimental results; (c) Simulation results [119]; (d) Double-sine-wave corrugated plate [123].

Although the sine-wave corrugated beams have excellent energy absorption capacity during crushing, it also produces a high initial peak force. As a good energy absorber, the peak force must be kept below the threshold. Otherwise, it may cause severe injury to the passengers. Thus, a trigger mechanism is employed to initiate a stable crush and decrease the peak force. One of the most common approaches is the chamfer trigger to guide a failure process [120, 121], and another way is to introduce eccentricity by removing some plies or replacing the plies with a weaker one [122]. However, some experimental results indicated that the triggers are not always functioning well in terms of controlling the initiation of crushing process. In an effort to eliminate the disadvantages, Jiang and Yang [123] proposed a novel metallic double-sine-wave beam as shown in Fig. 10d. It has another curvature along the out-of-plane direction compared with the traditional straight sine-wave beam. The results show that the double-sine-wave corrugated beam has a lower initial peak force and load uniformity. Afterwards, Hou et al. [124] developed a double-sine-wave corrugated square tube by introducing the sinusoid corrugation into every cell wall, and the new design has the ability of decreasing the initial peak force and strengthening the stability of the load-displacement curve.

3.5. Emerging energy absorbers

In addition to the common energy absorption structures mentioned above, some other kinds of emerging structures have been developed as promising candidates in the design of novel energy absorbers for airplanes or helicopters. For example, origami is an ancient art that can develop elaborate 3D structures by folding 2D structures along the predefined crease lines, and now it is widely recognized as a promising method for the mechanical metamaterial design [125]. The application of origami technology in the creation of novel energy absorbers has also emerged in recent years such as open-section origami beams [126], origami pattern tubes [127-129], and Ron Resch origami structures [130]. Fig. 11a-c present some typical origami structures that may be used in energy absorption devices. The origami structures would fail along the predefined pattern during the crushing process. Thus, these structures have a stable and controllable deformation mode. The predefined crease lines can be regarded as the grooves that result in a smaller peak force, and these crease lines also are the plastic hinge lines that dissipate the impact kinetic energy in the event of a crash. Also, deployable energy absorbers have drawn much attentions in the crashworthiness design of aerospace structures owing to the space limitation and weigh reduction. The deployable energy absorbers have advantages over the traditional energy absorbers in large available stroke and little occupied space. In case of urgency, it will deploy into a large energy absorption device by a predefined actuator. Kellas and Jackson [131] developed a deployable honeycomb structure that initiated the deployment by some flexible hinges located at the cell wall junctions, and drop experiments of a retrofitted fuselage section demonstrated that the deployable structures could absorb most of the impact kinetic energy. Hu et al. [132] designed a fan-shaped deployable energy absorption structure that was a square cell when deployed completely while a hexagonal cell when deployed partially as shown in Fig. 11d. Xing et al. [133] studied the energy absorption capacity of a fan-shaped deployable energy absorber with a single cell under quasi-static crushing as shown in Fig. 11e, and the influence of yield strength, Young’s modulus and the tube thickness on the crushing behaviors was also discussed.

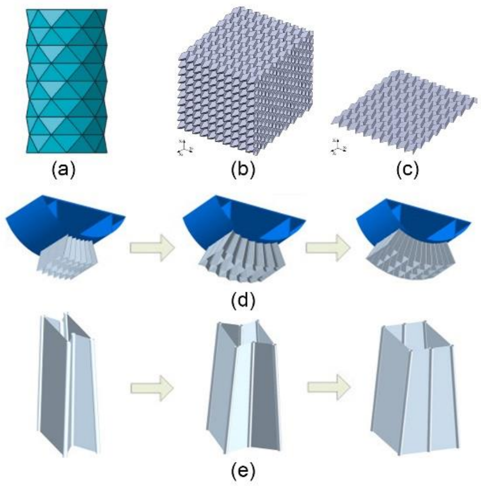


Fig. 11. Emerging energy absorbers: (a) origami tube [134]; (b) origami metamaterial [135]; (c) Miura-origami sheet [135]; (d) fan-shaped deployable structure [132]; (e) single cell of fan-shaped deployable structure [133];

Traditional energy absorbing devices convert the impact kinetic energy into inelastic energy by plastic deformation, fragmentation or dislocations. Unfortunately, these energy absorbers can only be used once owing to permanently damage and irreversible energy conversion. However, helicopter or aircraft may suffer from repeated impacts during take-off and landing. It requires much time and labor to reinstall a new energy absorber in a short time. Thus, the reusable energy absorber (REA) has become the urgent need to replace the traditional energy absorption structures. A frequently-used strategy to design REA is taking advantage of the mechanical buckling of the bistability of the straight or curved beams [136-138]. The beams will turn into a higher energy but steady configuration subjected to quasi-static compression or impact loading, the applied energy can be stored in an elastic manner during the beams as shown in Fig. 12a. Surprisingly, the beams can recover to its original configuration when applying an appropriate reverse force. An alternative method to develop new metamaterials for REA is by the dry friction between sliding objects such as granular materials. As shown in Fig. 12b, the continuous contact and friction between the rigid cylinders or sphere are promising methods to dissipate the impact kinetic energy. The rigid cylinders or sphere can be evolved from one stable configuration to another one, and only elastic deformation occurs for the rigid objects during the crushing. Thus, the impact kinetic energy can be converted into elastic energy and heat by friction [139].

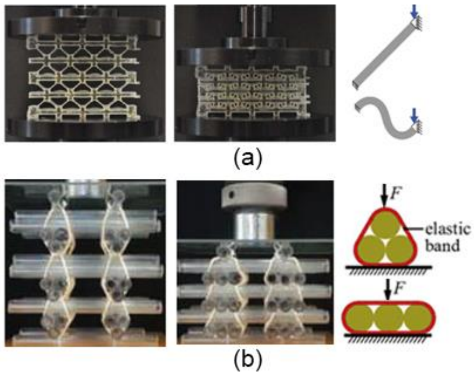


Fig. 12. Reusable energy absorbers:

(a) buckling-based REA [136]; (b) friction-based REA [139].

4. Crash dynamics of typical helicopter structures

4.1. Landing gear

Compared with the traditional fixed-wing aircraft, the distinctive characteristic of helicopters is the inherent flexibility in landing around complex surroundings. However, landing in stressful scenarios with various potential dangers may result in hard landing or crash landing, which will lead to serious structural failures or injuries to the occupants. Landing gear are the first structural component when helicopters touch the ground. Thus, it is desirable for the landing gear to absorb the impact kinetic energy as much as possible in the event of emergency landing or crashing. Fig. 13 presents the crash behavior of helicopter landing gear under an emergency landing. Landing gear of oleo-pneumatic type are frequently used for most aircrafts, which are composed of a gas spring and an oil damper. Crashworthiness design of landing gear is essential for the helicopter security and two representative crashworthy criteria are summarized [140]: (1) In order to avoid penetration into cabin or fuel system which may result in secondary damage, the failure mode of landing gears should be controllable during a crash; (2) landing gear should dissipate as much energy as possible to mitigate the overloads transferred to the aircraft and passengers. In the former case, a collapse mechanism triggered by the shear-pin failure is designed for the nose landing gear to prevent secondary hazards. The structural pin will collapse at the predefined failure load and then the nose landing gear can crush into the wheel well. Otherwise, the gears may collapse and then penetrate into the cockpit or the fuel system, leading to secondary damage or injury to the occupants. In the latter case, the energy absorption is mainly dependent on the damping force of the landing gear at the early contact with the ground. However, the damping force will increase sharply with the increasing of the sinking velocity, leading to a decrease of energy absorption efficiency in the event of a hard landing. Thus, damping force reduction should be designed appropriately to improve helicopter crashworthiness during a hard landing. Under normal circumstances, the crash orifice stays closed by a preloaded spring. However, it can be opened when the spring is compressed by the increased internal pressure during a high-speed landing. Then, the additional oil can pass through the crash orifice, leading to the reduction of damping force finally. In order to overcome the shortcoming of the traditional passive shock absorber, a semi-active landing gear damper based on magnetorheological fluid is developed to enhance the adaptive shock mitigation capacity [141, 142]. For example, Choi et al. [143] presented the design analysis and control of the adaptive magnetorheological landing gear dampers to obtain a desired stroking load over a desired sinking rate range, aiming to achieve enhanced energy absorption performance. Saleh et al. [144] compared the dynamic responses of three different landing gear systems including a regular landing gear, a passive viscous landing gear damper and a magnetorheological landing gear damper by a single degree of freedom helicopter model. Among the three different types of landing gear systems, the landing gear equipped with a mass-spring-magnetorheological energy absorber has the capacity of meeting a broad range of energy absorption requirements.

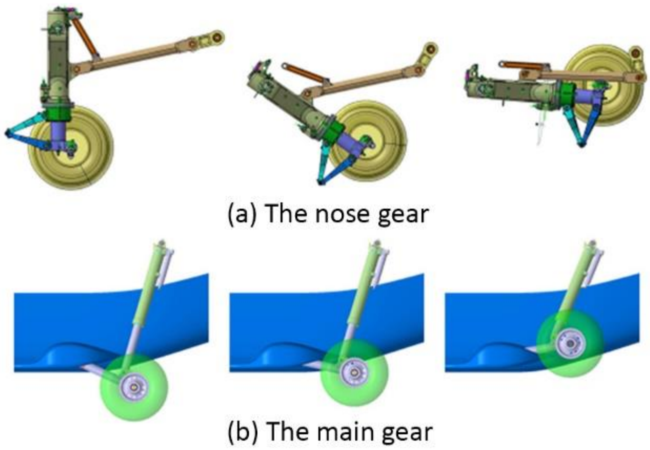


Fig. 13. Crash behavior of helicopter landing gears [140].

However, the excessive damping load may cause catastrophic failure of the landing gears in the event of a crash. Thus, additional energy absorbing structures should be implemented to prevent the landing gear from damage. During a crash, the plastic deformation of landing gear can absorb a portion of impact kinetic energy. Landing gear systems with a well-designed energy absorber can significantly improve helicopter structural crashworthiness [145, 146]. The crashworthiness requirements of MIL-STD-1290 presented the modern design criteria for current military helicopters, and some new criteria were added such as the higher sink speeds, pitch-roll attitudes and crash force mitigation requirements [147]. In order to improve the helicopter landing gear crashworthiness, energy absorption devices such as thin-walled metallic or composite tubes are widely used in the crashworthiness design of helicopter landing gear systems. For example, Airoldi and Janszen [148] proposed a design solution for a crashworthy landing gear by a novel triggering mechanism of metallic tubes as shown in Fig. 14a. A thin-walled aluminum tube was installed coaxially to the shock absorber cylinder, and the crushing of the metallic tubes under the severe crash condition can improve the energy absorption capacity of landing gear. A triggering mechanism can be activated under crash impact conditions, which has the capacity of reducing the initial peak force during collapse. As shown in Fig. 14b, Kim et al. [149] introduced a composite tube as an additional energy absorber to enhance the energy absorption capacity of landing gear during a crash. The quasi-static and dynamic crushing experiments were performed to study the failure process, and the simplified analytical model of the landing gear system indicated that the energy absorption performance could be improved by using the composite tubes. Guida et al. [150] adopted a carbon fiber reinforced as an extra shock absorber cylinder to improve the energy absorption capacity of the landing gear systems.

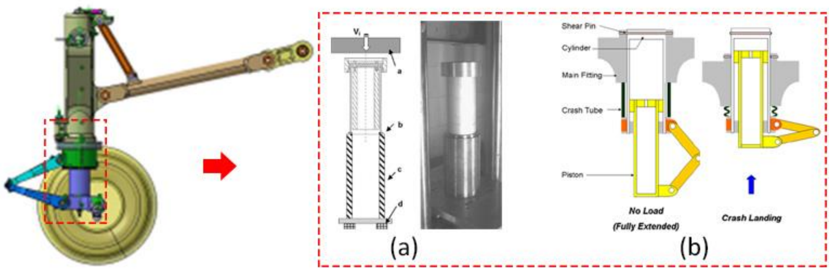


Fig. 14. Shock absorbers of helicopter landing gear [148, 149].

In the initial design stage for aircraft, some other landing gear systems of helicopters are also studied to meet different requirements. For example, helicopter skid landing gear can achieve equal effectiveness compared with traditional landing gear equipped with oleo-pneumatic shock absorbers [151]. The advantages of skid landing gear are the simple lay-out, light-weight and low cost. The energy absorption mechanism is dependent on the elastic or plastic deformation of slender cross members which connect the skids to the fuselage structures. Kumar et al. [152] presented the structural design and analysis of the skid landing gears by CATIA software. Airoldi and Lanzi [153] developed a multi-objective optimization method to seek a trade-off between the landing performance and structural strength of the landing gear. Tho et al. [154] conducted dynamic drop analyses of skid landing gear based on a nonlinear hollow rectangular beam element model, which brought the computational time for the hard impact simulation down to 12 minutes from 1~2 days. Shape memory alloys (SMA) are a new class of materials which can recover the original shapes by removing the external force or heating. It is also a likely candidate for the reusable energy absorption structures, particularly for the situation where large elastic deformation occurs. The development of helicopter smart landing gears based on a shape memory alloy may be also an alternative solution for energy absorption during hard landing or crash [155]. In addition, a robotic legged landing gear (RLLG) was also proposed to decrease the risks of structural failure or occupant injuries. Fig. 15 presents the landing process of a helicopter equipped with RLLG. Compared with the traditional landing gears, the shock absorber of RLLG has a larger stroke, leading to a much larger deceleration distance [156].

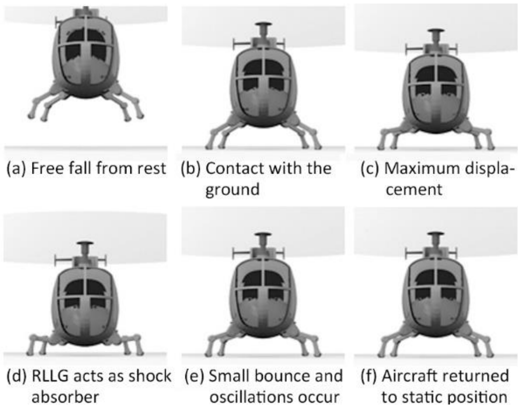


Fig. 15. Landing process of a helicopter equipped with RLLG [156].

4.2. Subfloor

Once helicopter landing gear lost the ability of load-carrying and energy absorption after the fractures happen, the subfloor structures have become the next prominent structural component to absorb the impact kinetic energy. Accordingly, the energy absorption performance of subfloor structures has to be designed properly so as to limit the peak deceleration and provide post-crash structural integrity of the cabin floor [157]. Fig. 16 presents the representative structural components of a helicopter subfloor which is composed of lateral bulkhead, longitudinal keel beams, and structural intersections. These structures are sandwich by the cabin floor and the outer fuselage skin [158]. Kindervater et al. [159, 160] firstly proposed a modular method to guide the design of subfloor structures. In terms of load-carrying and energy absorption capacity, the typical subfloor structural components such as the bulkhead, keel beams and structural intersections are optimized separately according to the modular method. Then assembling all the structural components into a complete subfloor structure. Generally, the energy absorption behavior of subfloor structures is influenced by the structural element, the connection between each part and the subfloor topology. Particularly, the structural intersections have a great influence on the crash response and energy absorption capacity of the subfloor structures. High peak loads are created by the stiff structural intersection, which can transfer excessively dangerous loading to the cabin floor and passenger seat.

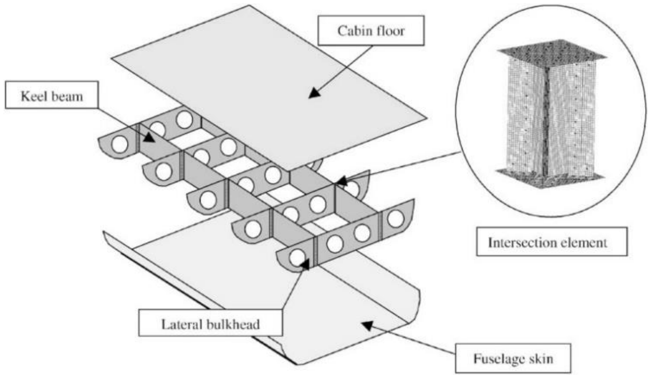


Fig. 16. Typical structural components of a helicopter subfloor [158].

Consequently, in order to satisfy the crashworthiness requirements of helicopter subfloor structures, the first step is to design an optimal structural intersection. The desirable crash response of a well-designed structural intersection should provide a proper initial stiffness and a stable crushing force after the initial collapse. A majority of research is focused on the dynamic mechanical response of the structural intersections. Bisagni [161] investigated the crash behavior and energy absorption capacity of a riveted intersection by experimental drop tests and numerical simulations. The riveted intersection was composed of two vertical webs and four angular elements, a closed square section was constructed with the diagonal formed by the two webs. Then, she conducted a research program to investigate the energy absorption performance of a subfloor structure in cooperation with AGUSTA Helicopter. The subfloor structure was composed of lateral bulkheads and longitudinal keel beams, and the two types of structural components were connected by cruciform intersection elements [158]. Subbaramaiah et al. [162] developed a retrofittable energy absorption device for metallic helicopter subfloor structures, a combination of metal and fiber reinforced composite layered structure was adopted to improve the energy absorption capacity and minimize the material corrosion. Compared with traditional retrofit solutions, the retrofits from the hybrid composite material can achieve better crashworthiness behavior with the minimal penalty to structural weight and fewer complications. Zhou and Wang [163] introduced the fold-core sandwich structures into the design of the intersection element, and the novel fold core can improve the impact mitigation capacity and reduce the structural weight.

In order to reduce the cost and structural weight, a dual function structural concept should be satisfied for the helicopter subfloor assemblage: load-carrying capacity for normal operation and energy absorption performance for impact protection. Thus, particular attention has to be given to the design of the beam webs and floor sections. Johnson et al. [164] described the design and fabrication of the composite beams and frame elements for helicopter subfloor structures, cost-effective fabrication methods such as autoclave technology, thermoforming and resin transfer moulding are introduced to fabricate these lightweight composite subfloor structures. McCarthy and Wiggenraad [165] conducted a detailed investigation of a composite helicopter subfloor structure which was composed of lateral and longitudinal sine-wave beams. One goal was to validate the reliability of the current crashworthiness simulation method for designing new composite structures, and the results indicated that the pre-test simulations could provide a reasonable overall solution with only coupon data. Joosten et al. [166] developed improved and innovative approaches for the design of crashworthy helicopter subfloor structures, a building block method including material characterization and large-scale crash test was adopted for the crashworthiness design of helicopter subfloor structures. Fig. 17 presents the experimental and simulation process of the building block approach. The experimental method coupled with a simulation methodology based on PAM-CRASH was developed to study the crash behavior and energy absorption mechanism of helicopter subfloor structures. Hughes et al. [167] conducted an experimental test of a box-beam subfloor structure dropped onto the hard surface to study the crash behavior of the metallic helicopter subfloor structure. Two limitations for the existing design of crashworthy helicopter structures were studied by observing the failure modes of different frame types and the mechanical performance of the intersection joints.

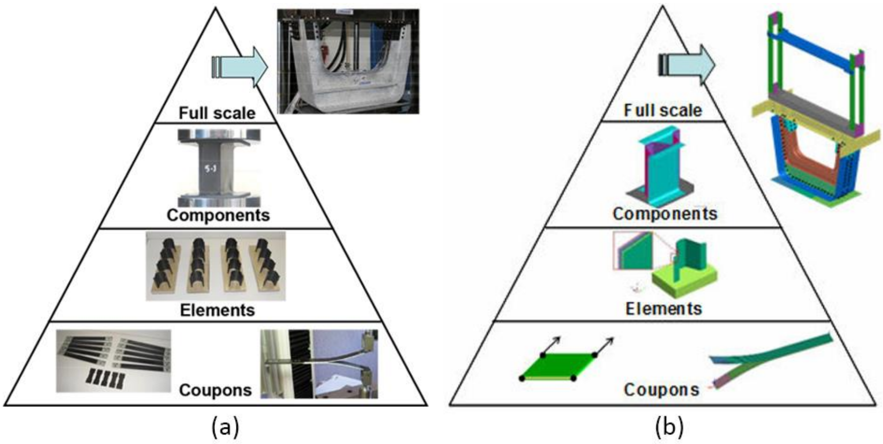


Fig. 17. Building block approach:

(a) Experimental test; (b) Simulation validation [166].

In addition, optimization procedures were also adopted to satisfy the crashworthiness requirements during the past few decades. For example, Bisagni et al. [168] developed an optimization procedure for helicopter subfloor components by the neural network method according to the crashworthiness requirements. The optimization procedure can be summarized in three steps. The first step defines the numerical model of the subfloor structural components, and the finite element analysis result is accepted as the input phase for the next step. The second step develops a parallel neural network to reproduce the crash response of the subfloor structural components. The third step is to seek for the optimal configuration by using the response surfaces calculated from the neural network. Then, a global strategy based on neural networks is used to evaluate the crash response of each subsystem. Fig. 18 shows the optimization procedure of a typical helicopter subfloor structure, the size variables such as dimensions, thickness and number of rivets and the topology variables such as the positions of the elements are also considered to achieve better structural crashworthiness. The objective function and constraint function are respectively the specific energy absorption and acceleration. Finally, the crushing force efficiency increased 12% and the mass of the subfloor structures decreased 4% [169].

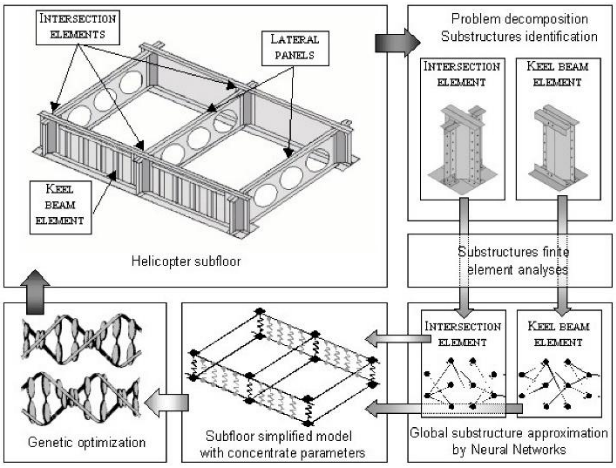


Fig. 18. Optimization procedure of a typical helicopter subfloor structure [169].

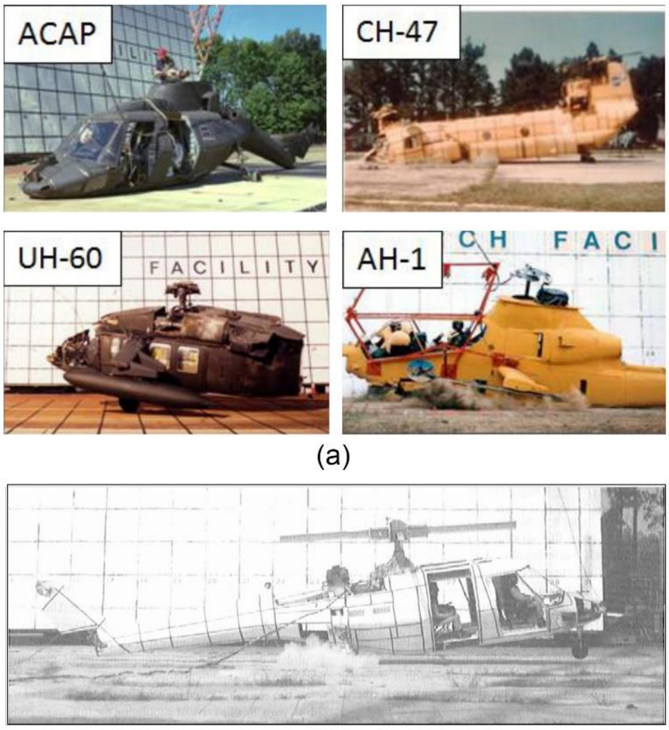


Fig. 19. Typical crash tests of helicopters and rotorcrafts [170].

4.3. Full-scale airframe

Full-scale crash testing is an important method to evaluate the crashworthy design of helicopters. However, only few full-scale crash tests were conducted during the past decades owing to long preparation period, high experimental cost and unrepeatable tests. Thus, a detailed experimental scheme should be made to obtain more structural response, which can be used to evaluate the helicopter crashworthiness and validate the numerical crash model. The Landing and Impact Research (LandIR) facility located at NASA Langley Research Center is a professional full-scale crash test facility where over 100 crash tests have been carried out on aircraft and helicopters. Some typical crash tests of helicopters including the ACAP, UH-1, CH-47, UH-60 and AH-1 were conducted at LandIR, and Fig. 19a shows these typical crash tests of helicopters. In 1987, Sikorsky Aircraft conducted a full-scale crash test at the LandIR facility to evaluate the crashworthiness performance of the helicopter under the support of the Advanced Composite Airframe Program (ACAP) [170]. Fig. 19b shows a crash photograph of the Sikorsky ACAP helicopter during the impact test. 82% of the ACAP airframe structures were made of composite materials. The initial impact velocity was 39ft./s with 10° pitch up and 10° roll left impact attitudes. In 2010, another two full-scale crash tests of a MD-500 helicopter were also carried out at the LandIR facility at NASA Langley research center. One test used a MD-500 helicopter whose lower outer skin was covered with an external energy absorbing honeycomb, and the other test used a MD-500 helicopter without any energy absorbing structure. There were three objectives for conducting this test: the first objective was to evaluate the crashworthiness characteristics and dynamic responses of a small representative helicopter; the second objective was to provide experimental data to validate the finite element model of helicopter crash simulation; the third objective was to validate a deployable energy absorption concept on an actual airframe structure [171]. The results show that the helicopter with the energy absorption honeycomb has smaller vertical impact acceleration, lower risk for occupant injury probability and minimal airframe damage, and Fig. 20 shows the MD-500 helicopters before and after the crash tests [172]. In order to increase the survivability of the occupants and minimize the risk of injuries during a crash, three drop tests of the Bell UH-1D helicopters were conducted at CIRA's test facility LISA under the support of the European project 'HeliSafe TA'. Three Martin-Baker helicopter seats and three dummies which respectively represented the pilot, forward and side facing passengers were used in the crash tests as shown in Fig. 21. The helicopter was lifted by the LISA truss and then released freely from a predefined height to impact with the ground. The on-board data acquisition units from CIRA and Siemens Restraint Systems (SRS) were installed on the helicopters. Some non-critical helicopter parts such as the gear box and the engine were replaced by metal structures with equal mass [173].

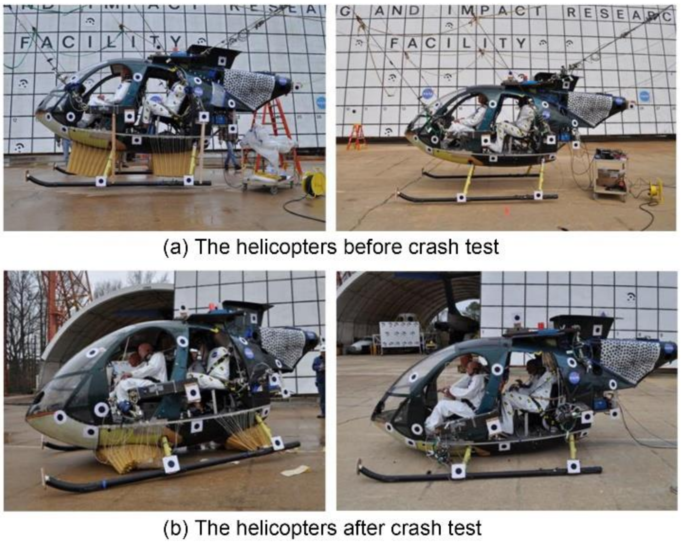
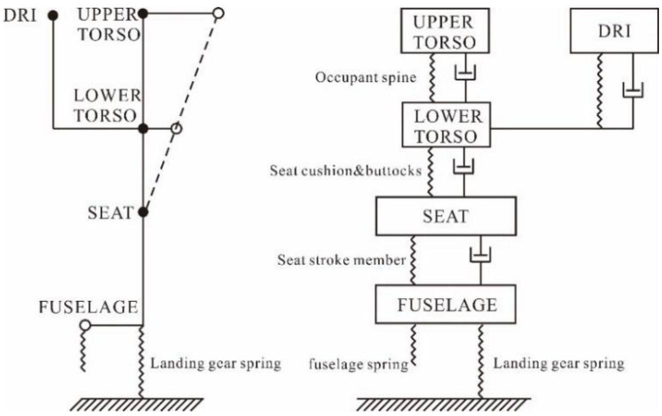


Fig. 20. The MD-500 helicopters before and after crash tests [172].

Fig. 21. Drop tests of the Bell UH-1D helicopters [173].

Development and validation of the computational/analytical methods to simulate the helicopter crash behavior and predict the structural response are important issues for crash certification by analysis. During the helicopter preliminary design, the computational/analytical tools can provide more detailed data such as the seat and occupant responses under impact loading. Compared with the full-scale crash tests, a majority of crash scenarios can be simulated with lower economic cost. The US Army initially initiated a research plan to develop a kinematic crash analysis code called KRASH as shown in Fig. 22a. It was actually a semi-empirical model in which the airframe structures were simulated by lumped masses, beams and springs. The simple five-mass model was used for the KRASH code at the initial stage, and the model could represent the main landing gear, an occupant and a crew seat. The model can provide the systematic stroke and load requirements during the preliminary design, the simplicity of the model results in economical and rapid analysis time which could aid in making timely design decisions [174]. However, the simple KRASH model can only predict the vertical impact response and it neglects the possible effects of structural characteristics and helicopter configuration on the response of the occupants. Thus, the detailed KRASH model as shown in Fig. 22b was also developed to contain enough modelling elements. It also has the capacity of simulating nonsymmetrical rolling and yawing impact conditions. The Grumman DYCAST finite element nonlinear structural dynamic computer program was a mathematical code which could be also used to conduct the crash simulations for helicopter design. The typical helicopter structures were discreted into nonlinear springs, stringers, beams and orthotropic thin sheet elements. The stiffness variance for helicopter structures was represented by plasticity and large deflections. The primary input data were numerical controls and options, motion constraints, geometry, material properties, applied load and rigid mass. The output data were respectively the printed displacement, velocity, acceleration, strain, stress and force [175]. In addition, Yang et al. [176] developed a simplified mechanical model to predict the maximum impact force during the crash and to guide the primary design of helicopter structures. The ratio of the dissipated energy absorbed by the landing gear to the total input energy and the kinetic energy decreasing curve of the fuselage during the crash can be obtained.



(a) Simple KRASH model

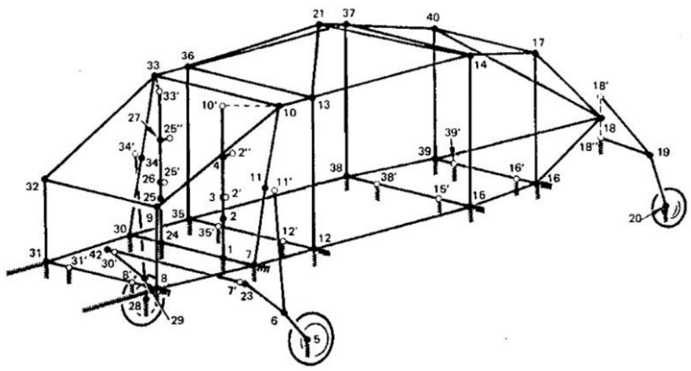

(b) Detailed KRASH model

Fig. 22. The kinematic crash analysis code KRASH [174].

Nowadays, the commercially explicit nonlinear dynamic finite element codes have matured and developed to simulate the highly nonlinear and transient crash response of helicopters subjected to the impact loading. These finite element codes, such as LS-DYNA, PAM-CRASH and MSC/Dytran, have already become useful tools to simulate the geometric and material nonlinear behaviors. For example, Lyle et al. [177] simulated a full-scale test of the Sikorsky ACAP helicopter using the explicit nonlinear dynamic code MSC. Dytran to analyze the impact response of composite helicopters. The finite element model was established by converting an existing NASTRAN model of the helicopter to a MSC/Dytran model. A two-stage modelling method was used in which a rigid structural model of the helicopter was executed during the deformation of the landing gear, the related data were output to a file about 0.05s before fuselage contact. Then, these data were regarded as the input information for the flexible model simulation [178]. Mikhailov and Fayzullin [179] conducted a simulation for emergency landing of a helicopter fuselage by explicit time integration using the central difference method. The finite element model has the ability to evaluate the loading conditions of the fuselage structure and analyze the overload in the connection zone of the passenger seat. Fasanella et al. [180] developed finite element models using explicit nonlinear dynamic code LS-DYNA to study a helicopter crash with an externally deployable composite honeycomb. It was focused on the finite element simulations of two full-scale impact tests involving the deployable energy absorbing structure: a mass simulator and a MD-500 helicopter with the retrofitted deployable energy absorbing structure. Annett [181] established a more detailed finite element model of the full-scale crash test of an MD-500 helicopter as shown in Fig. 23. The finite element model was composed of the fuselage, skid gear, seat, dummy and deployable energy absorbers. Full-scale mass simulations were carried out to develop confidence with regard to analysis and test methodologies.

Fig. 23. Finite element models for the full-scale crash test of an MD-500 helicopter [181].

4.4. Helicopter seats

In addition to the landing gears, subfloors and fuselages, helicopter crashworthy seats also play a crucial role in crash survivability. Harsh hard landings or accidental crash of helicopters may lead to severe injury to the occupants. Limiting the impact force can reduce the possibility of injury and minimize the risk of spinal fracture and paraplegia. The pioneering work on the crashworthiness design of helicopters was conducted by the Aviation Crash Injury Research Division of the Flight Safety Foundation. At the early stage of crashworthiness analysis for helicopter seats, much attention had been paid to determine the cause of the crash rather than the cause of injury. Thus, there was little knowledge about the injury causing mechanism. However, restraining the occupant, keeping the seats attached to helicopter structures and limiting the impact loads were deemed to have the ability to reduce the risk of injury. It was not until the 1960s and early 1970s that some novel concepts and criteria were developed for the design and qualification of helicopter crashworthy seats. Nowadays, the crashworthy seats have been widely used in almost all modern helicopters in the world. At present, crashworthy seats can be divided into four types according to the energy absorption devices used in the helicopter seats [182]. Firstly, the fixed load energy absorbers (FLEA) are one of the most extensive devices which exhibit a fixed approximately constant force-displacement characteristic. At the initial development stage of the crashworthy seats, the characteristics of longer energy absorption stroke and a stable load are strictly demanded for the helicopter seat design. There is no doubt that a structure with a constant load can provide a stable energy absorption process. The typical helicopter crashworthy seats that use FLEA include the Simula seats (Fig. 24a-c), Martin Baker seats (Fig. 24d-e), Fischer seats (Fig. 24g) and IAI seat (Fig. 24f). The energy absorption components of Simula seats are an inversion tube, the wire bender or the crushable tube. In the event of a crash, the reaction load increases almost linearly until reaching the peak force, then keeping a stable loading as the stroke progresses until the impact energy is completely dissipated. Some examples adopting the Simula seats are the H-60 Black Hawk, the H-60 Seahawk and the AH-64 Apache. The Martin Baker seats use a tube-die or a metal cutting tube as the energy absorption components, and the energy absorption process of the Fischer seats is realized by the bending of a strap or sheet of metal. The

IAI seats use the tube-through-die device as energy absorption components, and a stable load-displacement characteristic can be achieved by the flatten process of the tube-through-die devices. However, the disadvantage of FLEA is that the lighter occupants may experience spinal injury due to the crash load and heavier occupants are at a higher risk of bottoming out. The second generation of crashworthy seats is composed of two types that both are proposed to improve the efficiency. The first type is the crashworthy seat with the variable load energy absorbers (VLEA), whose limit load can be adjusted according to the occupant weight. VLEAs have the ability to match the occupant's weight and these new seats can also provide the maximum protection for all the occupants of different sizes. The load-displacement relationship can be adjusted to any value within the acceptable tolerance limit. The typical examples of the helicopter seats with VLEA are V-22 (Fig. 24h), Japanese OH-1/OH-X (Fig. 24i), UH-1Y (Fig. 24j), RAH-66, EH101, CH-53 and SH-3. The second type is the crashworthy seat with the fixed profile energy absorbers (FPEA), which is developed to provide protection for the occupants with an adjustable stroking force. PFEAs have a fixed single profile load-displacement characteristic and it can enhance the stroking efficiency of the helicopter seats. This type of crashworthy seat is more attractive to civil helicopter operators due to the fact that less available space is required in the helicopter cabin. The FPEA approach was adopted by the helicopter suppliers such as Fischer (Fig. 24k) and Skyline (Fig. 24l). The third generation of the crashworthy seats uses the Advanced Energy Absorbers (AEA), which attempted to contain all the excellent characteristics of the first two generations. Firstly, the new system will weigh the occupant and set the reasonable limit force according to the weight of the occupant. Then, the occupant will be decelerated with a special nonlinear force-displacement characteristic.

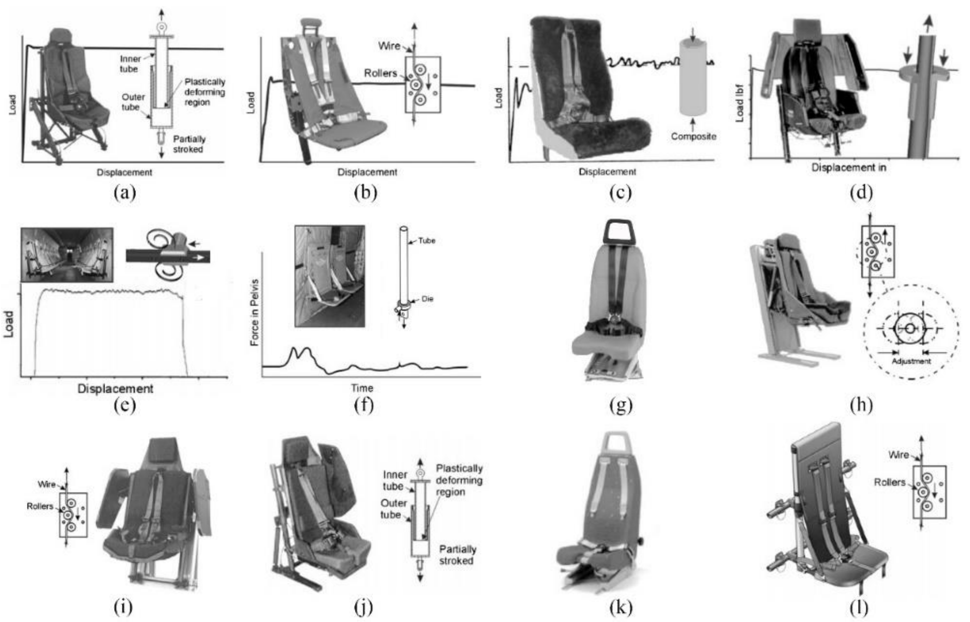


Fig. 24. Different types of helicopter crashworthy seats: (a) UH-60 Black Hawk seat, FLEA; (b) EH101 Foldable troop seat, FLEA; (c) Bell 230/430 pilot seat, FLEA; (d) A129 Italian (Agusta) seat, FLEA; (e) CH-53 troop seat, FLEA; (f) V-22 Osprey troop seat, FLEA; (g) Bell 230/305 medical attendant seat, FLEA; (h) V-22 Osprey armored seat, VLEA; (i) Japanese OH-X seat, VLEA; (j) UH-1Y seat, VLEA; (k) Bell 230/260 pilot seat, FPEA; (l) UH-1Y troop seat, FPEA [182].

With regard to the crashworthiness analysis of helicopter seats, the analytical methods are difficult to predict the crash dynamics accurately. The large deformation, strongly nonlinear behaviors, and strain rate effects are also the main challenges to reproduce the crash response of helicopters by numerical simulations. Nevertheless, numerical analysis can be regarded as a useful tool for the primary design of helicopters. For example, Cacchione et al. [183] proposed a hybrid model by finite element method and multi-body dynamic approach to study the crash behavior of helicopter seats. By the hybrid modelling method, the overall dynamic behavior of the crashworthy seat can be obtained by the multi-body dynamic, and the detailed stress and strain information can be obtained by the finite element analysis. Özturk and Kayran [184] performed dynamic simulations using ABAQUS to investigate the dynamic behavior and energy absorption characteristics of a crushable energy absorber system. This work is a preliminary study to evaluate the feasibility of energy absorption mechanisms based on plastic deformation of the aluminum legs of the helicopter seat during a crash. However, the full-scale crash test is a prominent method to investigate the crashworthiness of helicopter seats [185]. Hu et al. [186] conducted a full-scale drop test of a helicopter crashworthy seat to study the energy absorption performance and analyze the influences of different crash conditions on the human response. In order to reproduce the crash process, a multi-rigid body simulation model was established by the commercial code MADYMO integrated with LS-DYNA, which proved to be an effective tool to evaluate the crash response and human tolerance. Fig. 25 presents the experimental device, numerical model and crash response of the full-scale drop test of a helicopter crashworthy seat.

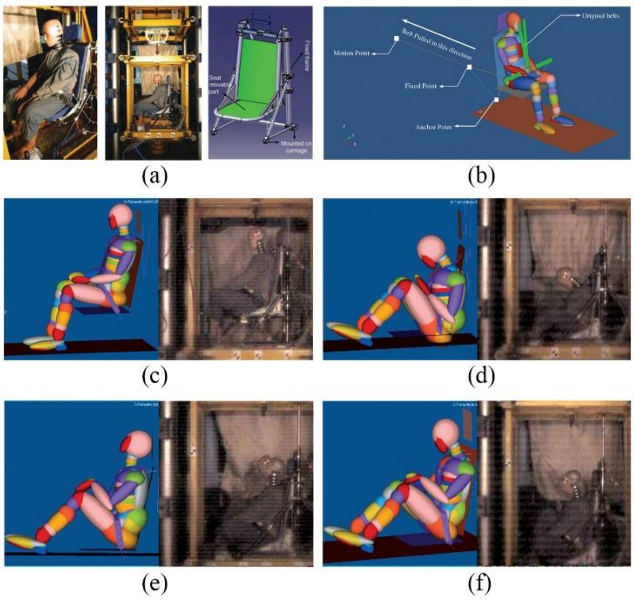


Fig. 25. Full-scale drop tests of a helicopter crashworthy seat: (a) Experimental device; (b) Simulation model; (c) t=0; (d) t=97s; (e) t=290s; (f) t=final time [186].

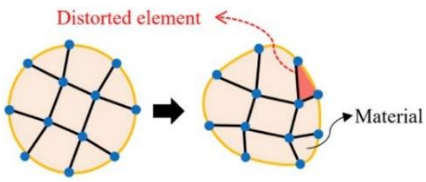
Some other studies were mainly focused on enhancing the energy absorption capacity of the helicopter seats by additional subsystems. For instance, a seat cushion is a prominent subsystem of helicopters with regarding to the impact protection in the event of a crash. The acceleration transmitted to the torso of the occupants can be reduced if the seat cushion is designed properly. Owing to the direct interaction between the occupant and seat cushion, the seat cushion must be comfortable and it must provide enough safety to the occupants. Polyurethane foam was the most frequently-used energy absorption material for seat cushions, and the seat cushions' performance must be validated by the dynamic sled tests according to the requirements of Federal Aviation Administration (FAA) before installation [187]. Helicopter seat cushions are always exposed to extreme environments with varying temperature ranges during their life time, and the temperature variation has a strong influence on the dynamic mechanical behavior of the polyurethane foam materials. Thus, it is critical to acquire the dynamic properties of the seat cushions at extreme temperature ranges [188]. In addition, the graded honeycomb shock absorber and carbon-based dampers are also regarded as energy absorption systems to provide better protections for the occupants [189, 190]. Another main subsystem of helicopters with regarding to the crash protection is the seat belts. The dynamic response of a seat belt restraint system also has important influences on the safety of occupants. The effectiveness of a seat belt system must be strictly evaluated during the crashworthiness design [191]. Besides, the search for the feasible region is a useful method to determine the portion of the domain where design variables can be adjusted to satisfy the requirements of performance and regulations. In view of this, a new method was proposed to determine the feasible region for the survivability zone of a crashworthy helicopter seat [192].

4.5. Fuel tank

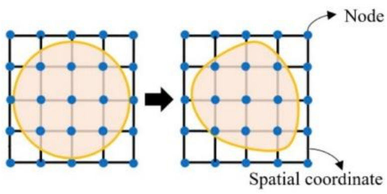
The main function of a fuel tank is to store and provide fuels for helicopters under normal flight conditions. However, many casualties in army and civilian helicopter accidents were caused by fires ignited following a crash owing to the fuel leakage by the tank failure in the event of a crash. Thus, the structural design of a fuel tank is of great importance in the crashworthiness design for helicopters, and a good crashworthy design is essential in preventing dangerous injuries during a crash. The fuel tanks are usually designed to withstand a drop impact with an initial velocity of

19.81m/s without leaking or spilling fuel. Besides, US Army regulations for fuel tank crash performance have also claimed to eliminate the injuries and fatalities to smoke fire. Thus, military helicopters are designed with fire suppression systems including self-sealing shut-off values in the fuel lines. Nowadays, these systems virtually play an important role in eliminating fire and smoke in military helicopter accidents [193]. The FAA has passed the Re-Authorization Act of 2018 to require all newly-manufactured civilian helicopters to have crash-resistant fuel systems [194].

Generally, impact tests are the major method to evaluate the dynamic properties and failure behaviors of the crashworthy fuel tank. During the drop tests, the fuel tanks were lifted to a preset height by a crane, then released freely and dropped onto a specialized force plate to obtain the load-time history. The damage and failure behaviors of a helicopter fuel tank can be observed after the drop test. Since the 1960s, a detailed military specification was issued by the US Army which defined the necessary crashworthiness requirements for helicopter fuel tanks [195]. It was also demanded that the drop impact test must be performed to evaluate the crash response of fuel tanks. Furthermore, the specification also provides that fuel leakage is not allowable when a fuel tank filled with water drops from the height of 19.8m. In addition, the numerical simulation of the crash response for helicopter tanks is another prominent method used in primary crashworthiness design, which can significantly reduce the economic cost of the drop tests of full-scale fuel tanks. The crash response of a dropped fuel tank is a typical fluid-structure interaction (FSI) problem with strong nonlinearity and large deformation [196]. The Arbitrary Lagrangian-Eulerian method (ALE) which combines a Lagrangian structural model with an Eulerian fluid mesh to solve the FSI problem [197, 198]. In terms of the Lagrangian method, the movement of the continuum is the function of time and material coordinates, which means that the nodes of the Lagrangian mesh deform together with the material, leading to element distortion during the large deformation analysis. However, the movement of the continuum is the function of time and spatial coordinates for the Eulerian method. The materials move freely through Eulerian meshes and element distortion will not happen. Fig. 26 shows the diagrams of the Lagrangian and the Eulerian model. Using the ALE method, the Lagrangian approach is mainly applied to the solid structures while the Eulerian method is mainly applied to the fluid structures. The information of boundary conditions between the Lagrangian and the Eulerian elements is exchanged for the ALE method. Although the calculation time of ALE simulation is longer than that of the Lagrangian simulation, ALE can produce more accurate results for FSI problems. The smoothed particle hydrodynamic (SPH) method also provides a useful tool to model FSI problems for helicopter fuel tanks. SPH is actually a Lagrangian-based method and the large-scale features can be captured by tracing the particle movements. The large deformation and strong nonlinearity can be properly solved owing to the non-fixed connectivity between the particles [199, 200].



(a) Lagrangian method



(b) Eulerian method

Fig. 26. Diagrams of the Lagrangian and the Eulerian method.

Typically, there are several key factors in evaluating the structural soundness of helicopter fuel tanks such as the crash impact analysis, sloshing analysis, bird strike analysis and ballistic impact analysis. According to the experimental test specifications and simulation methods, a majority of research work were completed on the crashworthiness analysis of helicopter fuel tanks [201, 202]. For example, in order to analyze the energy absorption capacity of the textile layer and protection frame, Luo et al. [203] investigated the crash response of the fuel tanks with and without the protection frame when dropping on the ground with an initial velocity of

17.3m/s. It could be proved that the protection frame was necessary to improve the crashworthiness of the fuel tank. Zheng et al. [204] analyzed the dynamic behaviors of a naked flexible tank and a dual layer fuel tank by ALE method during the impact with ground. The inner and outer layer of the dual-layer fuel tank were respectively the woven fabric composite material and the metal material. More attention was focused on the connection positions due to the fact that the bolt and connector hole patch were the maximal principle stress zones. The dual-layer fuel tank demonstrated better crash behavior compared with the naked flexible tank. According to the test specifications of MIL-DTL-27422, Kim and Kim [205] performed numerical simulations of the crash impact tests of rotorcraft fuel cells based on the SPH method. The maximum stress primarily appeared on the top and bottom metal fittings, especially on the top metal fittings of the feeder cells and bottom metal fitting of the after-fuel-cell. Thereafter, they conducted the numerical simulations of a crash impact test of a helicopter external auxiliary fuel tank base on ALE modeling techniques to evaluate the failure behaviors of the fuel tank mounted inside the composite container in the event of a crash [206]. Yang et al. [207] conducted the crash impact tests of the nylon woven fabric composite fuel tank, and an FSI finite element model was also established to analyze the dynamic failure behaviors. The effects of the impact angle, impact velocity, the fuel tank thickness and the liquid volume fraction were investigated according to the finite element analysis. Fig. 27 shows the effective stress and water pressure of the fuel tank filled with 50% water. Prus et al. [208] conducted the impact simulations of a drop test from the height of 20m for an elastic fuel tank reinforced with a polymer exoskeleton. The fluid and air inside the fuel tank are modelled by SPH method and the calculations were performed by the nonlinear RADIOSS solver. In addition, a number of studies were concerned on the sloshing of the helicopter fuel tanks based on FSI. For example, Anghileri et al. [209] established the numerical models for the water sloshing in a fuel tank during the impact with the ground by finite element, Eulerian, ALE and SPH method. Kim et al. [210]

investigated the drop impact-induced damage of a helicopter fuel tank in consideration of the liquid sloshing.

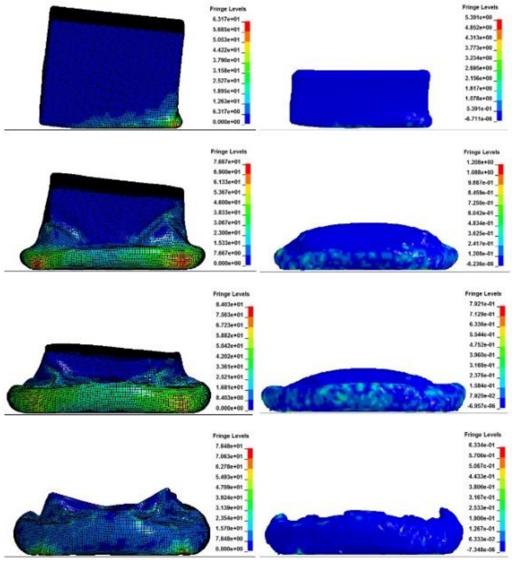


Fig. 27. Effective stress and water pressure of the fuel tank filled with 50% water [205].

When helicopter fuel tanks suffer from penetration by a high-velocity projectile, the kinetic energy of the projectile will be transferred to the surrounding structures through the fluid, which may lead severe damage and failure to the fuel tanks. This catastrophic phenomenon is named as Hydrodynamic Ram (HRAM) [211]. A number of threats can lead to HRAM, resulting in aircraft damage such as the ballistic projectiles and fragments caused by the missile detonation. An example of the typical scenarios caused by HRAM is the Concorde accident which happened in 2000. Fig. 28 shows the penetration process of a fluid-filled tank by a high-speed projectile. The penetration process is usually classified into three stages [212]. In the first stage, a high-pressure shock wave is produced from the impact zone after penetrating into the fluid-filled tank, and it continues to propagate through the tank. In the second stage, a radial pressure field is created by the projectile when decelerating through the fluid, and it is related the impact velocity and geometry of the projectile. In the final stage, significant pressure pulses are generated owing to the expansion and collapse of the cavity, and the projectile exits from the fluid-filled tank. A majority of studies have been conducted to investigate the HRAM. Since the 1970s, various research groups such as the Naval Postgraduate School and Naval Weapons Center carried out a number of analytical and experimental investigations on HRAM [213]. These works mainly focused on the pressure prediction at different stages, the FSI description and the structural response of the containers. Numerical simulations have also been widely used to study the HRAM phenomenon [214-216]. The ALE and SPH methods are capable of simulating the cavity evolution, pressure variance and container deformation. In addition, some other researches were mainly concentrated on the attenuation the HRAM effect on the fuel structures [217, 218].

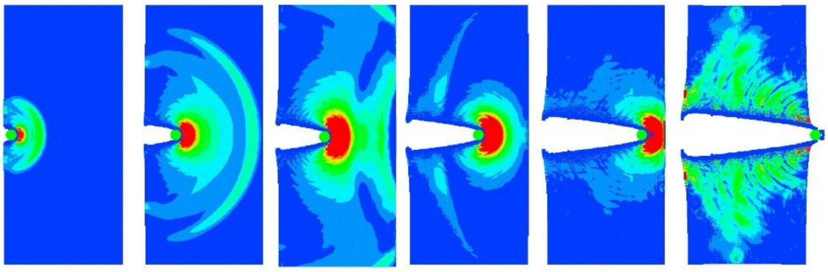
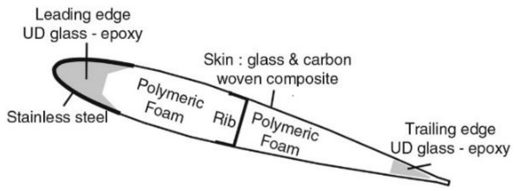


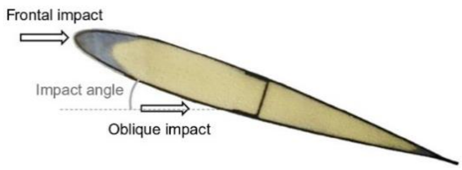
Fig. 28. Penetration process of a fluid-filled tank by a high-speed projectile.

4.6. Helicopter blade

Helicopter blades are typical sandwich structures that operate in a state with high rotation speed. Generally, a blade is composed of a leading edge, a skin, a polymeric foam, a trailing edge and a protection layer [219]. Fig. 29 shows the schematic section and material components of a general blade. The leading and trailing edge are made of glass-epoxy unidirectional composite materials, and the skin is usually constituted by two or three plies of glass-epoxy and carbon-epoxy woven fabric. The protection layer covering the leading edge is made of stainless steel. Besides, some ribs made of carbon-epoxy composite materials are used to stabilize the skins. A blade is a crucial structural component during the flight of a helicopter since the failure and damage of a blade may lead to catastrophic accidents during impact. Thus, understanding the impact damage and failure mechanism of a helicopter blade is essential to the structural integrity of helicopter structures. The impact source can be classified into the soft impactors (birds, hailstones) and hard impactors (stones, ballistic projectiles and fragments dropping from helicopters). Furthermore, two representative impact scenarios, the normal impact to the leading edge and oblique impact on the lower skin of the blade, are summarized according to the accident statistics. The impact velocities can range from a few meters per second to several hundred meters per second which are dependent on the rotational speed of the helicopter blade, and the impact angle varies over a wide range owing to the inclination of the blade during a flight.



(a) Schematic section and components.



(b) Frontal and oblique impacts.

Fig. 29. Structural components and impact conditions of
a general helicopter blade [217].

A majority of research has been conducted on the dynamic behaviors of sandwich structures subjected to impact loadings. However, limited studies have focused on the impact failure mechanism of helicopter blades. Most research mainly focused the ballistic impact performance of helicopter blades. Morozov et al. [220] studied the impact damage resistance of helicopter laminated blades under impact loading using combined analytical and experimental methods. The influence of the projectile size on the damage tolerance of a helicopter blade was studied, and it was proved that the maximum allowable defect size was dependent on the projectile size. Rasuo [221] investigated the survivability of a helicopter tail rotor blade after the ballistic damage caused by 7.9mm caliber shoulder weapons. The vulnerability and survivability of the helicopter tail rotor were evaluated according to vibratory and fatigue testing. Impact damage investigations of helicopter blades were also conducted with different incident directions and positions. Kumar et al. [222] conducted a multi-scale finite element analysis to study the dynamic behaviors of typical composite main and tail rotor blades under the low-velocity impact loadings, and the upper surface of the blades were impacted by a projectile with a vertical impact velocity. The initiation and growth of the damage in crucial components were captured, and a parametric investigation was conducted to study the impact damage behaviors. Tawk et al. [223] conducted experimental tests and numerical simulations to study the ballistic behaviors of a helicopter blade subjected to a frontal impact which is shown in Fig. 30. It could be observed that the damage initially occurred during the front surface, then a plastic deformation occurred for the protection layer with the rise of the impact energy level, which may result in the delamination in the skin-foam interfaces. Furthermore, the penetration induced damage to the roving by cracking of the resin, led to the slipping of the packages of fibers during the impacted zone. Navarro et al. [224] studied an oblique impact on the skin of helicopter blades by experimental tests, a semi-continuous modeling technique was proposed to study the damage mechanism of the woven skin in a blade.

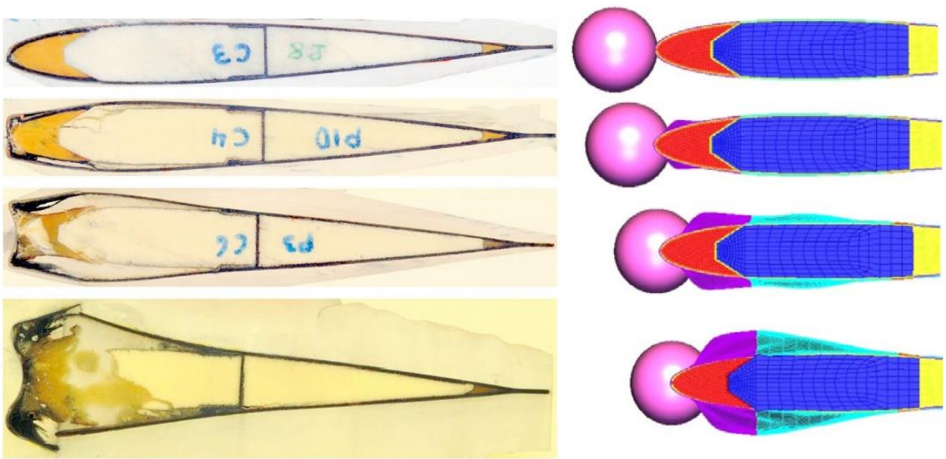


Fig. 30. Experimental and numerical results of a blade subjected to the frontal impact [221].

Table 1. Struck and damaged structural parts by bird strikes for helicopters.

	Struck		Damaged	
Windshield	Number	Percent (%)	Number	Percent (%)
Rotor	283	35	150	39
Nose	165	20	43	11
Fuselage	91	11	44	11
Radome	77	9	26	7
Tail	21	3	11	3
Light	9	1	8	2
Engine	24	3	3	1
Landing gear	10	1	4	1
Other	109	14	76	20
Total	815	100	384	100

5. Representative helicopter crash scenarios

5.1 Bird strike

Bird strike is a complex impact dynamic behavior which occurs in an extremely short-time. The response of bird strike is characterized by transient and high intensity dynamic load, strong non-linearity, large deformation, soft impact and high strain rate [225]. Thus, a collision with a bird may result in serious structural damage to aerospace structures. During the period of 1990-2009, 491 of the 99420 reported bird strikes to civil aircraft have occurred for helicopters, and 242 caused damage and 69 caused substantial damage to the helicopters. Table 1 presents the number and percent of strikes and damages caused by bird-strikes on the different structural parts of helicopters [226]. The early experimental tests on the bird strike were conducted by Wilbeck in 1977 [227]. However, high costs and time-consuming procedures of the bird-strike tests were challenging for the aircraft design. Numerical simulations provide a good tool to investigate the dynamic mechanical behaviors of aerospace structures subjected to bird strike, and most simulations were conducted by Lagrange, ALE or SPH methods. As shown in Table 1, since the windshield is the most vulnerable structural item and has a high percentage of bird strikes for helicopters, it is extremely important to analyze the dynamic behaviors and impact damage of helicopter windshields. Hedayati et al. [226] conducted the bird strike analysis on a typical helicopter windshield based on SPH method, and five types of lay-ups in a windshield with single layer glass, single layer stretch acrylic, two-wall cast acrylic, glass with PVB interlayer and acrylic with PVB interlayer were studied to prevent the bird from perforating the windshield. It was proved that PVB interlayer was capable of increasing the strength of the windshield and PVB was also a good choice used in a windshield to protect against bird strike. Hu et al. [228] developed a FE-SPH model to investigate the impact damage mechanism of a helicopter windshield subjected to a bird strike. A full-scale bird strike test was carried out to validate the crashworthiness performance. A bird strike test strike onto a flat plate was performed to obtain the accurate parameters to develop the bird constitutive model. Fig. 31 shows the experimental and numerical results of a bird strike on helicopter windshield. Based on the experimental and numerical results, a new structural design was also performed to improve the structure stiffness and crashworthy behaviors.

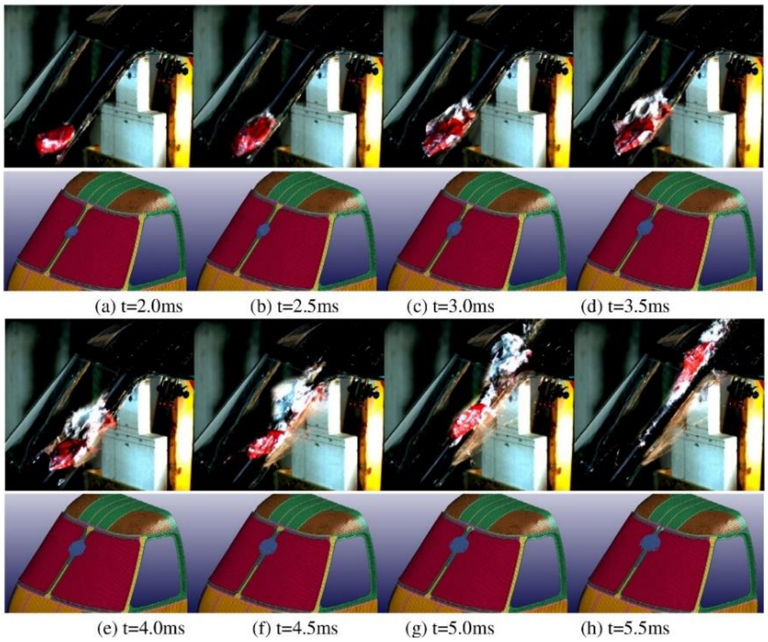


Fig. 31. Experimental and numerical results of a bird strike on a helicopter windshield [226].

The helicopter blades, operating in a state with high rotational speed, are also extremely vulnerable to bird strike during flight. Once the serious damage and failure of blades occur, the lift force, propulsion and control can't be provided by the rotating wings, leading to catastrophic helicopter accidents. Therefore, it is of great importance to investigate the dynamic behaviors of a helicopter blade impacted by a bird. For example, Eren et al. [229] simulated the dynamic response of a composite helicopter blade subjected to a bird strike in which the bird was modeled using SPH method and a suitable equation of state. A hemispherical-ended cylindrical bird strike test on a flat plate was also conducted to validate the bird model. It should be noted that a helicopter blade with a rotational velocity showed different stiffness behavior and bird strike response. Naik and Kumar [230] presented the modelling technique of a bird striking on the root end of a main rotor blade. The impact damage to the main rotor blade root end was dependent on the bird size, bird orientation with respect to hitting location, blade size, blade rotational speed, blade span wise location of impact and the helicopter cruise speed. In addition, the dynamic behaviors of a bird strike were also studied on other aerospace structures. For instance, Heimbs et al. [231] investigated the bird strike response of a searchlight and its pod on a military helicopter. Fig. 32 shows the numerical models of a bird striking on a searchlight and its pod. In order to obtain accurate results, the searchlight pod and the internal electrical components were also modeled in details. A number of loading cases were defined such as a bird striking on the searchlight, the frame of the searchlight, the searchlight pod and the related attachment structures. It was concluded that the central bird strike on the center of the searchlight pod was the most serious loading case. Jang and Ahn [232] conducted a bird-strike study and a preliminary design of a composite radome structure. The bird strike response of the attached structure that supports the radome was also investigated by SPH method. It was concluded that the structural stability of the radome and antenna structures after the optimum design was secured by the numerical results of the SPH method.

Fig. 32. Numerical modelling of a bird striking on searchlight and its pod [229].

In general, the helicopter fuel tanks are usually arranged at the rear or on the bottom of the occupant compartment. However, in order to increase the cruising range, an auxiliary fuel tank is installed outside the helicopter. In addition to the previously introduced crash impact tests, the damage and failure behavior caused by bird strikes should be analyzed during the primary design of helicopters. The leakage of a helicopter fuel tank after a bird strike could lead to survivability issues for the occupants. Kim and Kim [233] performed impact simulations of a bird strike on an external composite auxiliary fuel tank to reveal the most vulnerable conditions. Shell elements were used for the fuel tank while the fluid and bird were modeled by SPH method. The maximum stress and failure index of the composite fuel tank filled with 50% and 85% water were obtained at different locations including the bottom, upper, center and outer edge. Furthermore, the bird strike response of a commercial KUH-1 Surion utility helicopter fuel tank was evaluated to study the dynamic behavior and damage. The SPH method was used to model the impact properties of a bird, and the coupled Lagrangian-Eulerian method was employed to replicate the sloshing of the fuel and the interaction between a composite tank and the fuel. Fig. 33 presents the bird strike model of the KUH-1 Surion utility helicopter fuel tank. The results indicated that the curved geometry and the increase of the fuel inside the tank would increase the damage risk of the composite tank [234]. The impact-induced damage behaviors of the auxiliary composite fuel tank for the Korean Utility Helicopters was also studied. The Hashin failure criteria was used to predict the damage of the composite materials. The local damage and failure in the vicinity of the impact center increased with the growing of the amount of fuel owing to the repulsive force resulting from the inertia of the fuel tank [235].

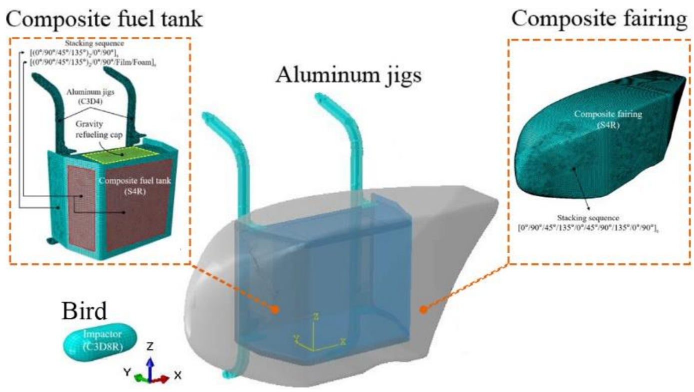


Fig. 33. Bird strike model of the KUH-1 Surion utility helicopter fuel tank [232].

5.2 Water impact

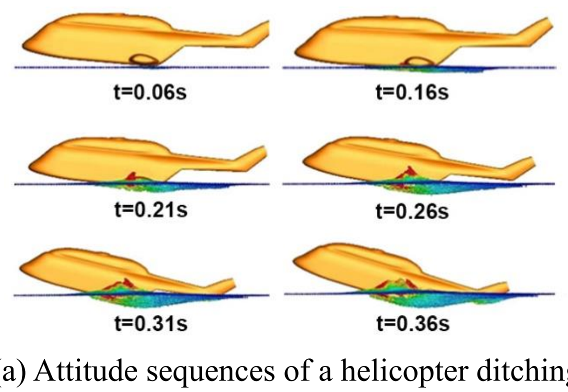
Water impact of helicopters is a serious crash scenario. According to the helicopter crash database established by the National Transportation Safety Board (NTSB) between 1981 and 2011 in the Gulf of Mexico and Hawaii, 133 helicopter crashes into to water had occurred, 26% of occupants lost their lives and 38% were injured during these accidents [236]. During a hard surface impact, impact kinetic energy of the helicopter was absorbed by the plastic deformation of the metallic structures or the matrix cracking, debonding and fiber breakage of composite materials. The impact load and acceleration can be decreased to a survivable level by energy absorption of the landing gear, subfloor structure, crashworthy seats and the restraint system. However, the energy absorption mechanism of a helicopter water impact is completely different from that of a hard surface impact. The landing gear and conventional subfloor structures behave poorly in absorbing the impact kinetic energy and transmitting the water pressure. The energy absorption is mainly dependent on the membrane and bending behavior of the skin and the plastic collapse of the attached structures. Thus, the failure of the skin is not allowable during a water impact due to the fact that it will reduce the flotation capacity of helicopter airframes and the internal structure may suffer from the secondary damage owing to the water entry. The typical water impact-induced damage and failure of helicopters are extensive skin damage, weakened flotation capability, rivet failure, airframe distortion/failure, windshield damage and tail boom separation. The earliest work in the field of water entry was dated back to 1929 when the first analytical model was developed by Von Karman to predict the loads during a rigid seaplane float impacting into water [237]. An important review about helicopter ditching was published during the period of 1982~1989, and it was mainly focused on two issues. The first one involved the investigation of the impact and post impact conditions [238], and the other one evaluated the structural response on occupant injury and numerical modelling techniques of water impact [239]. Seddon and Moatamedi [240] presented a review of water entry of aerospace structures, providing a systematic introduction of the experimental, numerical and theoretical research progresses that occurred between 1929 and 2003. Particularly, Hughes and Campbell [241] provided a chronological review of helicopter water crashworthiness related to the theoretical, experimental, and numerical progress and accomplishments from 1982 to 2006. In summary, this research was focused on three aspects: structural component drop tests, full-scale drop tests and helicopter ditching.

During a water impact of a helicopter, the landing gear doesn't encounter any resistance and it absorbs little impact kinetic energy. Thus, most of the impact kinetic energy must be dissipated by the sub-floor structure to protect the occupants from injury. The energy absorption capacity of regular sub-floor structures performs poorly during a crash in water compared with a crash on the ground, and it was also concluded that the energy absorbed by sub-floor structures was of the same order as impact kinetic energy transferred to the water [242]. The traditional sub-floor structures of helicopters must be re-designed to satisfy the energy absorption requirements during a water impact. Large transverse pressure forces are exerted on the bottom skin when a helicopter hits the water, and the metal skin panels tend to rack along the rivet lines with large plastic deformations. In order to characterize the water impact response, a complete section-by-section analysis of a subfloor was conducted experimentally and numerically [16]. Two design conceptions were proposed to improve the crashworthiness requirements for the future helicopter design: increasing the maximum deflection of the skin without failure can contribute to transfer the load to other energy absorption structures, decreasing the stiffness of the intersection joints due to the fact that the load during a water impact was lower than that during a hard surface impact and the collapse load would not be reached if the joints were too strong. In order to address the problem, a tensor skin was proposed to improve the crashworthiness of subfloor structures during a water impact [243]. The skin is allowed to withstand a large deformation and the load can be transferred to the beam of the subfloor successfully. Furthermore, a new structural design of a helicopter sub-floor was developed to dissipate the impact kinetic energy for both hard surface impact and water impact, and it could exhibit different energy absorption modes depending on different impact conditions [244]. The upper part of the subfloor structure was very strong and stiff so as to provide impact resistance for the occupants during a hard surface impact. However, the subfloor structure must have a lower failure strength during a water impact, and it was achieved by a tube cutting through the bottom of the sub-floor structure and penetrating into water. In addition, some research was also conducted to analyze the other helicopter structures on water impact. The influence of crashworthy seats on the helicopter underwater egress during a water impact was investigated [245], and the dynamic behavior of a filled tank integrated in a helicopter subfloor during the impact with the ground and with the water were studied by numerical modeling methods [246].

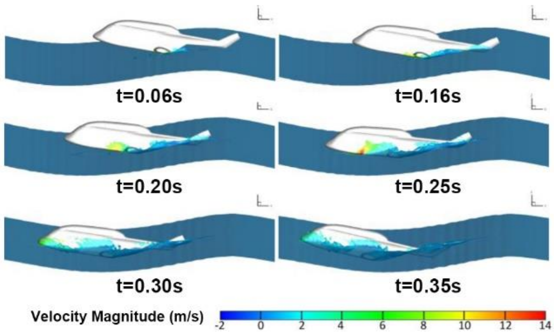
The experimental tests and numerical simulations of the full-scale drop response were also prominent approaches to asset the crashworthiness of helicopters in the event of a water impact. As shown in Fig. 34, Pentecote and Vigliotti [247] conducted drop tests and numerical simulations of a full-scale WG30 impacting on water with a vertical velocity of 8m/s. The investigation was composed of two sections, the first one was focused on the description of the testing instrumentation, the measurements included the pressures, accelerations at different locations and related data obtained from sensors. Then, an overall description of the crash sequence during the water impact was introduced in detail. The second one was mainly devoted to the numerical simulation based on PAM-CRASH to replicate the impact process under the real test conditions. It was observed that the helicopter overturned a few seconds after the impact, nearly no deformation had occurred for the landing gear. Randhawa and Lankarani [248] developed a finite element model of a UH-1 helicopter using the ALE method to simulate the dynamic response of a helicopter impacting into water. The occupant kinematics, the lumbar load and the most crucial injury mode of the dummy were also investigated in the helicopter water impact model, and MADYMO was used to establish the occupant model.

Fig. 34. Crash sequences of a helicopter during a water impact [245].

An emergency landing of a helicopter on water is termed as ditching, and helicopter ditching is an extremely complicated physical phenomenon involving multi-disciplinary topics such as hydrodynamics, kinematics, stability and structural strength design. During the past few decades, analytical and numerical modelling methods are the major method to investigate the dynamic impact response and structural integrity of helicopters during ditching. The analytical methods include Von Karman's model based on momentum theory and Farhad's model based on linear potential flow theory [237, 249]. However, owing to the highly non-linear hydrodynamic properties and failure behavior of the helicopter, these theoretical models are not good enough to describe the realistic FSI mechanism in such a complex phenomenon. Fortunately, the numerical modelling techniques such as finite element method, ALE method, finite volume method, SPH method provide a better solution to predict the non-linear hydrodynamic response of a helicopter ditching. Xiao et al. [250] developed a weakly compressible SPH method coupled with six-degree-of-freedom dynamics to investigate the hydrodynamic and dynamic behavior of a helicopter ditching. A simple dummy particle wall boundary treatment method was used to address the geometrically complex engineering problems, and an OpenMP memory-shared parallelization integrated with Z-curve particle reordering was implemented to accelerate the computation. Fig. 35a shows the attitude sequences of a helicopter during ditching with an incident angle of 6 degrees. Woodgate et al. [251] established the simulation model for an AW159 helicopter ditching based on SPH method, the cases of a vertical drop of the AW159 helicopter at sea-state zero and on the crew of a wave were simulated. Lu et al. [252] investigated the dynamic behavior of a helicopter during ditching on wavy water by solving the unsteady Reynolds-Averaged Navier-Stokes equation. The air-water interface was obtained by the volume of the fluid model, and a global moving mesh model was used to record the relative motion between the helicopter structure and water. The influence of water entering wave positions on the ditching characteristics was analyzed. It was found that crest and falling waves were the optimal water entering wave positions and the optimal pitching angle is 6 degrees in the event of a ditching. Fig. 35b shows the falling wave velocity contours of a helicopter ditching with a pitching angle of 10 degrees.



(a) Attitude sequences of a helicopter ditching
with an incident angle of 6 degrees [248].



(b) Falling wave velocity contours of a helicopter ditching with a pitching angle of 10 degrees [250].

Fig. 35. Crash responses of a helicopter ditching.

5.3 Occupant response and injury

The inertial forces generated from excessive accelerations may lead to severe injuries to the occupants during a crash. Occupant protection is mainly dependent on alleviating the impact load exerted on the human body. As such occupant responses have become a major indicator to evaluate the shock-induced injury. Thus, much attention has been paid to the dynamic responses of the occupants during a full-scale crash. For example, a full-scale crash test of the Sikorsky ACAP helicopter was carried out to provide experimental data for the correlation of the crash simulation model. In order to study the dynamic responses of the occupants, two crew seats, two troop seats and four anthropomorphic test dummies were used in the test [178]. Jackson et al. [253] presented the experimental occupant response data of the ACAP helicopter test, and the response data was correlated with the results obtained from the injury prediction models such as the dynamic response index (DRI) and the head injury criteria (HIC). A comparison was made between the occupant's vertical acceleration data and the Eiband whole-body acceleration tolerance curve. The overall injury assessment of the occupants indicated that a moderate to high level of injury risk was experienced during the ACAP crash test. Based on the experimental results of the Bell UH-1D helicopter crash test, a computational model was developed by the multi-body dynamic method and finite element analysis to investigate the occupant response and injury risk of the helicopter protective system such a pilot airbag and the harness [254]. The conventional MADYMO belts in combination with finite element belts with membrane elements were used for the modelling of harness systems. The belt segments that were in contact with the human body were modeled by the finite element method, while the conventional belt elements were used for the other areas of the harness system. Fig. 36 shows the occupant responses of the Bell UH-1D helicopter with the pilot airbag and harness protective system. It was proved to be effective to use simulation models to determine the safety concepts and structural characteristics of the harness system and airbag.

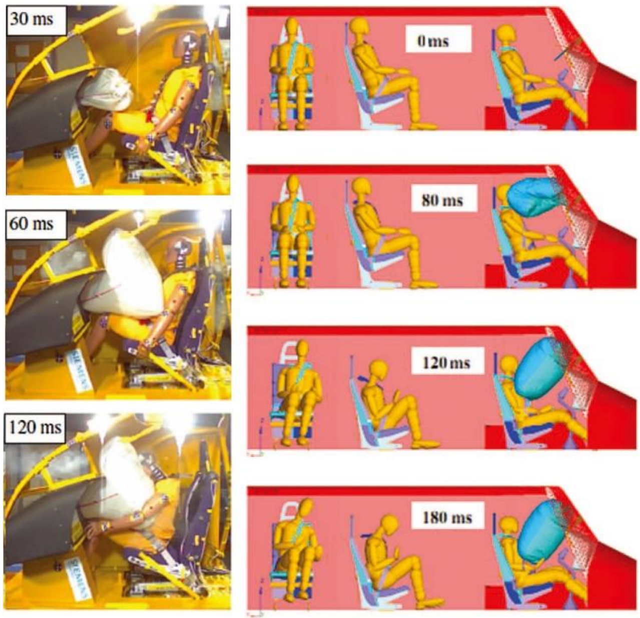
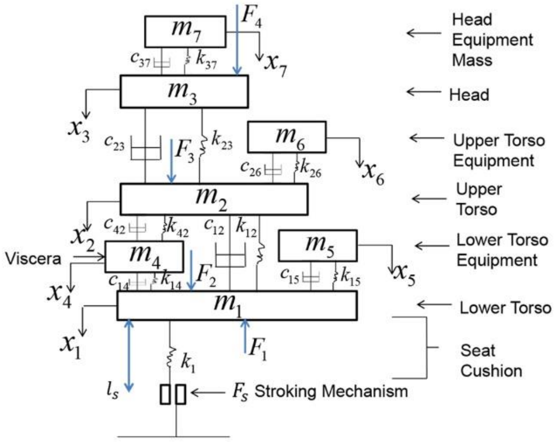
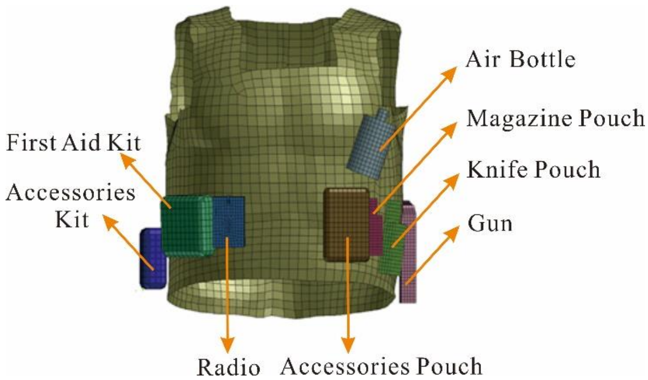


Fig. 36. Occupant responses with the pilot airbag and harness protective system [252].

In addition, the helicopter subsystems also have a great influence on the occupant's response and injury, For instance, Cheng et al. [255] theoretically analyzed the optimal performance of a helicopter seat cushion to evaluate the spinal injury during a crash. In order to obtain the minimum DRI, the seat cushion should guarantee that the spinal compression reaches its peak load quickly and remain fairly constant during the crash. However, the upper torso deceleration should reach its peak value and then keep at this level to acquire a minimal value of the maximum spinal compression load. A helicopter equipped with different energy absorption stages may also lead to significant injuries to the occupants owing to the mutual interaction among the stages. Thus, Astori and Impari [256] conducted an integrated analysis on the dynamic behavior of the subfloor crushing elements and the seat energy absorbers to optimize the occupant's response and reduce injury levels. In addition to the optimization, the response surface models were established and it was found that mechanical parameters of the seat and subfloor structure were related to seat stroke, subfloor deflection and the maximum lumbar spinal load. Generally, helicopter seats can provide enough energy absorption protection for the occupants with a specified mass range. However, the helicopter occupants must carry increasing amounts of equipment to meet their mission. In order to understand the influence of increasing mass on the survivability, Aggromito et al. [257] proposed a linear mass-spring-damper model with 7-degrees-of-freedom to simulate a helicopter occupant wearing body-borne equipment on a seat. Fig. 37a shows the occupant model with the attached equipment. It was proved that increasing the equipment mass would reduce the energy absorption capacity of the helicopter seat and increase the injury risks of the lumbar spine, hip, upper torso and head. Furthermore, a finite element model of a fully deformable 50th percentile Hybrid Ⅲ dummy carrying equipment and sitting on a helicopter crashworthy seat was developed to study the effect of the equipment location on the occupant injury [258]. The results showed that it would increase the lumbar load and the head's injury risk when the equipment was placed on the torso, while it would decrease the injury risk of lumbar and spinal region and provide a better protection for the neck and head. Fig. 37b shows the recommended configuration of the attached equipment according to the finite element analysis results. Finally, the seat suspensions have the ability to mitigate the impact load that transmits to the human body. There are three typical seat suspensions for all the helicopters: passive, semi-active and active. Choi and Wereley [259] studied the biodynamic response mitigation of the shock loads by using a magnetorheological (MR) seat suspension and established the MR seat suspension model for helicopters with a detailed lumped parameter model. It was shown that the passive and semi-active MR seat suspensions have better impact protection capacity compared with the passive hydraulic seat suspension. Singh and Wereley [260] investigated the effect of occupant's compliance on a vertically stroking helicopter crew seat suspension. The occupant compliance was an important factor in determining the internal biodynamic damping, which could dissipate a portion of impact energy.



(a) Theoretical model of the occupant with the attached equipment [255].



(b) Recommended configuration of the attached equipment [256].

Fig. 37. Occupant model and recommended configuration of the attached equipment.

6. Crashworthiness design requirements

The first military standard MIL-STD-1290 was issued to guide the crashworthy design of military fixed-wing light aircraft and helicopters [261]. The military standard mainly includes a series of passive safety regulations and these crash requirements are crucial to acquire better crashworthy design for the future vehicles. The helicopter structures such as the landing gear, subfloor structures, fuel system, crashworthy seats and restraint systems must be well-design based on the related regulations to obtained better crashworthiness performance. Generally, the following crashworthiness requirements must be satisfied: providing enough survival space for the occupants; the acceleration exerted on the human body must stay within an allowable level; avoiding the secondary damage to the occupants resulted by the falling off of airborne devices; avoiding penetration into cabin resulted by the blades or other sharp structures; preventing post-crash fire resulting from fuel leakage; available emergency escape route after the crash. Firstly, the crashworthiness requirements of landing gears can be summarized in two aspects [140]. The first one is that the failure mode of landing gears should be controllable so as to avoid penetration into cabin or fuel system which may result in secondary damage during a crash. This penetration can lead to serious damage to the occupant if the landing gear rupture and penetrate into the cockpit in the event of a crash. Accordingly, the structural pin is required to rupture at a predefined force and then the landing gear can collapse into the wheel well. The second one is that landing gear should dissipate as much energy as possible to mitigate the loads and accelerations transferred to the helicopter and passengers. The excessive damping force may lead to severe structural failure during a crash. Thus, additional energy absorbing devices must be implemented to absorb the impact kinetic energy. Besides, the energy absorption capacity of the landing gears must maintain the structural integrity of helicopters in case of a hard landing with a low impact velocity. Thus, the passengers have sufficient survival space, and the repair cost and time of the broken helicopter can be reduced greatly.

As the second line of defense, the main fuselage structures of helicopters are of great importance for the occupant's safety in the event of a crash. Crash accidents indicate that a majority of occupants die from the squeeze of the surrounding structures or the secondary impact-induced damage. Thus, the maximum deformation of the cabin is not allowed to exceed 15% of the original size. In order to absorb the impact kinetic energy and mitigate the shock load as much as possible, sufficient strength and excellent plastic deformation capacity are required for the fuselage structures. The subfloor is a priority during the helicopter crashworthy design. In order to improve the energy absorption capacity and reduce the structural weight, optimized energy absorption materials and structures should be employed in the subfloor structures. Another major threaten to the occupants during a crash is that the rotors may penetrate the cabin, leading to catastrophic damage and injury. Thus, reasonable structural design and material selection for the rotors are undoubtedly a prominent aspect for the helicopter crashworthy design. During a longitudinal impact condition, the survival space of the front cockpit may be insufficient owing to its large deformation, which will also lead to severe injury risk for the occupants.

Helicopter crashworthy seats and restraint systems are the final line of defense for the safety protection of the occupants. After energy absorption and shock mitigation of helicopter landing gear and fuselage, the remaining impact kinetic energy should be absorbed by the seat and restraint systems. Firstly, the crashworthy seat must be designed with enough strength so as to ensure that falling off and severe dislocation should not occur for the connection pieces when subjected to impact loading. It is also required that the seat system remains coordinated with the surrounding structures. An alternative method is that the bottom and back parts of the seats are respectively assembled with the floor and back of the cabin to balance the upper, lower and longitudinal loads. Energy absorption devices must be implemented into the crashworthy seat system to absorb the remaining impact kinetic energy. Enough survival space is required around the seat system so that the human body will not impact with the adjacent airborne equipment, which may lead to a potential injury to the occupants owing to the secondary impact. The design requirements for the military helicopter seats are described by JSSG-2010-7, which defines that the static and dynamic load tests are required for the military rotary-wing aircraft [262]. The occupant restraint system, consisting of a belt, aviation suit, helmet and the impact environment, is used to reduce the injury risk when the occupants impact with the surrounding structures. Special design regulations are set for the occupant restraint systems in the helicopter design. For example, rigid structures should be removed from the contact range of a head as far as possible. Energy absorbing material, smooth external surface and material strength should be reasonably selected for the console, instrument panel and other surrounding devices within the contact range of a head. Energy absorbing bushings should be designed for the upper and lower limbs, with sufficient strength for the structures around the foot operating systems. With regarding to the crashworthy design of fuel systems, the fuel tank should be installed far from the occupant zone or the areas where the fuel tank can be pierced by the surrounding deformed structures. The connection strength between the tank and the support structure should be satisfied. In order to prevent fuel leakage during a crash, the fuel tank material should have excellent ductility, energy absorption capacity and flame retardancy. The fuel lines should be designed in consideration of the crashworthiness requirements.

7. Conclusions and future research

The first-generation helicopters which are designed according to crashworthiness design requirements have been kept in service for many years. The idea of crashworthiness design for helicopters come from a series of accident surveys. It was found that majority of helicopters could survive from a crash if the cabin damage, fire and the collision between occupants and hard airframe structures are prevented. As helicopters usually have no effective ejection lifesaving system, it is extremely important for the helicopter to consider the crashworthy design and it is proved that survival rate of occupants in most catastrophic accidents has been remarkably raised by adopting the crashworthiness design principles. The present review summarizes the studies that were carried out throughout the last fifty years, which concerns with the crashworthiness design and energy absorption mechanism of helicopter structures. At the end of this article, some remarks are put forth as follows:

(1) Although the plastic performances of some typical structural components including rings, tubes, honeycombs and corrugated beams/plates are emphatically

introduced in the first section of the paper. It should be noted that both static and dynamic behavior of these classical and basic components have been studied for nearly one-hundred years, and a large number of papers have been published. This review may only cover a few of them. Due to their good energy absorption performance with simple manufacture and low cost, they are very popular structures that are adopted in aircraft crashworthiness design. However, the improvement of helicopter's crashworthiness is bound to come at the cost of the structure weight. But with the improvement of the requirement of lightweight structure, it becomes necessary to study some novel components with lighter weight and even better energy absorption behavior. Recent studies on metamaterial components and energy absorption components inspired by bionics provide many new ideas for the development of efficient energy absorption components.

(2) A controllable failure mode of landing gear should be designed to avoid penetration into the cabin or fuel system. It must dissipate as much energy as possible to mitigate the loads and accelerations transferred to fuselage structures; A well-designed structural intersection is of great importance for the crashworthiness design of helicopter subfloor structures, which can provide a proper initial stiffness and a stable crushing force after the initial collapse; In terms of the full-scale airframes, enough survival space and available emergency escape routes must be provided for the occupants after the crash. The secondary damage to the occupants resulting from the falling off of airborne devices must be prevented; Helicopter crashworthy seats play a crucial role for the occupants' survivability, restraining the occupant, keeping the seats attached to helicopter structures and limiting the impact loads are deemed to have the ability to reduce the risk of injury. The fuel tank must be designed properly to prevent post-crash fire resulting from fuel leakage.

(3) Although the evaluation of the bird strike responses is mainly dependent on the real physical tests, numerical simulation techniques show an increasing trend to replace the experimental test during a certification. The dynamic behavior of a helicopter water impact is completely different from that of a hard surface impact.

The energy absorption mainly depends on the membrane and bending behavior of the skin and the plastic collapse of the attached structures during a water impact. Alleviating the impact load exerted on the human body can provide protection for the occupants. The energy absorption strategy must be adopted by designing reasonable landing gear, subfloor and crashworthy seats.

With respect to crashworthiness design and energy absorption capacity of future helicopters, the authors suggest that further research may focus on the following topics:

- Design of the light-weight energy absorbing metamaterials based on the special microstructures.
- Mimicking natural materials to design novel light-weight structures with higher energy absorption capacity.
- Creating new damage tolerance evaluation criteria based on cloud computing and big date from the injuries of human organs.
- Developing a new generation of simulation methods and experimental techniques for helicopters by making use of artificial intelligence.
- Establishing structural integrity design criteria and technical approaches for helicopter survival space under high intensity crash.

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