Overview of the Transport Rotorcraft Airframe Crash Testbed (TRACT) Full Scale Crash Tests

Martin Annett

Research Aerospace Engineer

NASA Langley Research Center

Hampton, VA, USA

Justin Littell

Research Aerospace Engineer

NASA Langley Research Center

Hampton, VA, USA

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ABSTRACT

The Transport Rotorcraft Airframe Crash Testbed (TRACT) full-scale tests were performed at NASA Langley Research Center’s Landing and Impact Research Facility in 2013 and 2014. Two CH-46E airframes were impacted at 33-ft/s forward and 25-ft/s vertical combined velocities onto soft soil, which represents a severe, but potentially survivable impact scenario. TRACT 1 provided a baseline set of responses, while TRACT 2 included retrofits with composite subfloors and other crash system improvements based on TRACT 1. For TRACT 2, a total of 18 unique experiments were conducted to evaluate Anthropomorphic Test Devices (ATD) responses, seat and restraint performance, cargo restraint effectiveness, patient litter behavior, and activation of emergency locator transmitters and crash sensors. Combinations of Hybrid II, Hybrid III, and ES-2 ATDs were placed in forward and side facing seats and occupant results were compared against injury criteria. The structural response of the airframe was assessed based on accelerometers located throughout the airframe and using three-dimensional photogrammetric techniques. Analysis of the photogrammetric data indicated regions of maximum deflection and permanent deformation. The response of TRACT 2 was noticeably different in the horizontal direction due to changes in the cabin configuration and soil surface, with higher acceleration and damage occurring in the cabin. Loads from ATDs in energy absorbing seats and restraints were within injury limits. Severe injury was likely for ATDs in forward facing passenger seats.

INTRODUCTION

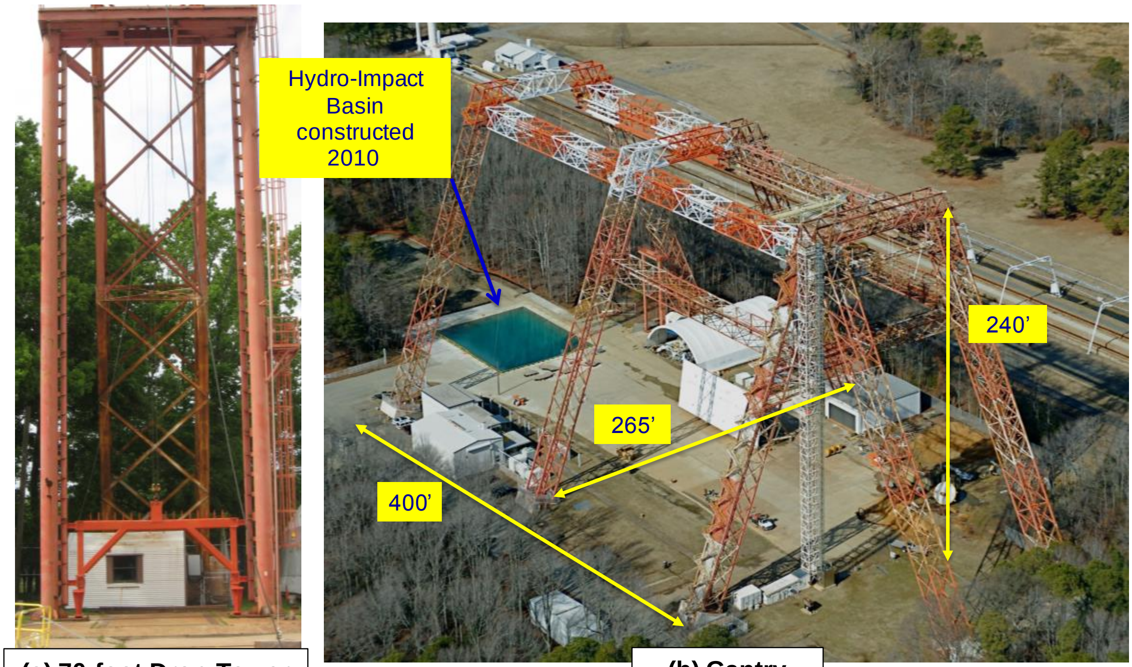
Full-scale crashworthiness of rotorcraft is considered differently for civilian and military classes. For civilian rotorcraft, the Federal Airworthiness Standard for transport category rotorcraft does not address crashworthiness at the airframe level [1]. A pair of idealized acceleration vs. time conditions is specified for evaluation of the seat and occupant. Crash sled testing with Anthropomorphic Test Devices (ATDs) must be conducted to determine seat structural adequacy and occupant survivability. The 95th percentile survivable impact velocities were determined from mishap data as 26-ft/sec vertical and 50-ft/sec horizontal [2] and the sled test conditions are, in some measure, based on these bounds. It is worth noting that the Federal Aviation Administration (FAA) is considering new guidelines to assess crashworthiness at the vehicle level [3].

Military crashworthiness requirements consider both the airframe and occupant response. The military crash safety standard for rotorcraft specifies occupant seat acceleration limits and occupied volume reduction constraints for seven crash impact design scenarios [4]. Compared to civilian data, military 95th percentile velocities are higher in the vertical (42-ft/sec) and similar in the horizontal directions. One design scenario includes significant components of velocity in both the vertical (42-ft/sec) and horizontal (27-ft/sec) directions.

With both civilian and military rotorcraft, it is important to consider the coupled response of the airframe and the occupants to impacts containing significant components of both horizontal and vertical velocity. Varying attitude, velocities, and terrain will alter the magnitude and duration of the airframe deceleration. The combination of landing gear stroke, subfloor crushing, floor and frame deformation, seat stroke, and restraint activation must all be taken in account.

For full scale testing, drop test articles can be oriented to introduce vertical velocities as well as lesser components of horizontal and lateral velocities. The flight path angle may not match the incidence angle with the impacting surface, and therefore not represent entirely the required impact condition. A guided rail drop can produce both horizontal and vertical velocities. However, horizontal velocity is limited by the rail length and how much potential energy is converted to horizontal velocity. The release from the end of the rail is also a freefall condition that may introduce errors in the attitude at impact.

NASA Langley Research Center's Landing and Impact Research (LandIR) facility has the select capability to conduct multiaxial crash or landing tests of airframes and landing vehicles into terrain, prepared surface, or water. The test article is lifted with steel cables as high as 200-ft and the lift cable is pyrotechnically released to swing like a pendulum onto an impact surface of water, concrete, or soil. Swing cables are configured to form a parallelogram to minimize pitch angular velocity during the pendulum swing. In order to simulate free flight conditions, just prior to ground contact, the swing cables are pyrotechnically severed from the test article. Critical interactions between the airframe, seat, and occupant can be evaluated based on synthesis of high speed and high definition video and sensors. A photo of the LandIR facility, otherwise known as the "Gantry," is shown in Figure 1.



(a) 70-foot Drop Tower

(b) Gantry

Figure 1. Landing and Impact Research Facility

TRACT TEST ARTICLE DEVELOPMENT

NASA’s Revolutionary Vertical Lift Technology (RVLT) Project and its predecessor Rotary Wing (RW) Project have supported crashworthiness research to improve capabilities and acceptance for current and future rotorcraft [5]. The Transport Rotorcraft Airframe Crash Testbed (TRACT) research program was started in 2012 by the RW Project, with these primary objectives:

- Evaluate the integrated airframe, seat, and occupant response under a combined horizontal and vertical impact velocity.
- Assess improvements to occupant loads and flail envelope with the use of crashworthy features such as pre-tensioning active restraints and energy absorbing seats.
- Provide data for comparison to finite element analyses.
- Evaluate the response of composite energy attenuating subfloors under severe but survivable conditions.

- Evaluate advanced biofidelic ATDs
- Develop novel techniques for photogrammetric data acquisition to measure occupant and airframe motion.

Requests for participation were circulated with the Federal Aviation Administration (FAA), Department of Defense (DOD), and rotorcraft industry manufacturers. For the first crash test (TRACT 1), formal agreements were established with the following collaborators:

- The Naval Air Systems Command (NAVAIR), Human Systems Department, Crashworthy Systems Branch, Patuxent River, MD. NAVAIR develops, evaluates, and qualifies systems for Naval Aviation intended to prevent injury resulting from impact-based aviation mishaps.
- The FAA Civil Aeromedical Institute (CAMI), Aeromedical Research Division, Protection and Survival Laboratory, Biodynamics Research Team. CAMI conducts research concerning occupant impact protection in civil aircraft. To evaluate the protection provided by seats and restraint systems, the team develops new testing protocols, test dummy modifications and new injury criteria.
- The U.S. Army Aeromedical Research Laboratory (USAARL), Warfighter Protection Division, Injury Biomechanics Branch. USAARL investigates air and ground warfighter response to dynamic loading, including blast, ballistics, and impact.
- Cobham Life Support develops restraint systems for fixed and rotary wing and ground vehicles.

Upon completion of TRACT 1, preparations for the crash test of the second CH-46E airframe began. Agreements with the TRACT 1 collaborators were extended for participation in TRACT 2. Additional agreements were developed and instituted with two organizations:

- The Australian Cooperative Research Centre for Advanced Composite Structures (ACS) and the German Aerospace Center (DLR) conduct research in airframe retrofit technologies for improved crashworthiness.
- The U.S. Army Cargo Helicopter Project Management Office (CARGO PMO) supports CH-47 Chinook systems development and acquisition.

Other crash sensor manufacturers and seat manufacturers also developed safety systems and components with the TRACT collaborators.

Two CH-46E airframes were obtained from the Navy CH-46E Program Office (PMA-226) at the Navy Flight Readiness Center in Cherry Point, North Carolina. The CH-46E airframe was chosen as a candidate testbed because of its common applicability as a medium-lift rotorcraft with airframe dimensions comparable to a regional jet or business jet. The CH-46E airframe design is semi-monocoque with skin stiffeners and frame sections. The cabin airframe cross section is nearly uniform from fuselage stations (FS) 190 to 320, and is composed primarily of aluminum 2024 and 7075 alloys. The CH-46 has no keel beam and its longitudinal stiffness comes from the floor and cargo rails. A photograph of one of the CH-46E airframes is shown in Figure 2.

Figure 2. CH-46E Airframe

There were several key modifications to the airframes prior to conducting the TRACT tests. Fiberglass panels were attached to the underside of the cockpit enclosure to reduce plowing of the exposed cockpit. Two angle channel beams were bolted along the outer sidewalls three inches above the waterline to provide hard points for the swing and pullback cables. The location of the beams was chosen to keep the windows accessible and visible. The hard points on the beam were selected to ensure proper spacing for a parallelogram swing, and align the cables near the center of gravity (CG). A stochastic pattern of 1-inch dots was applied to the airframe skin on the left side for use in a technique called full-field photogrammetry. These modifications are shown in Figure 3.

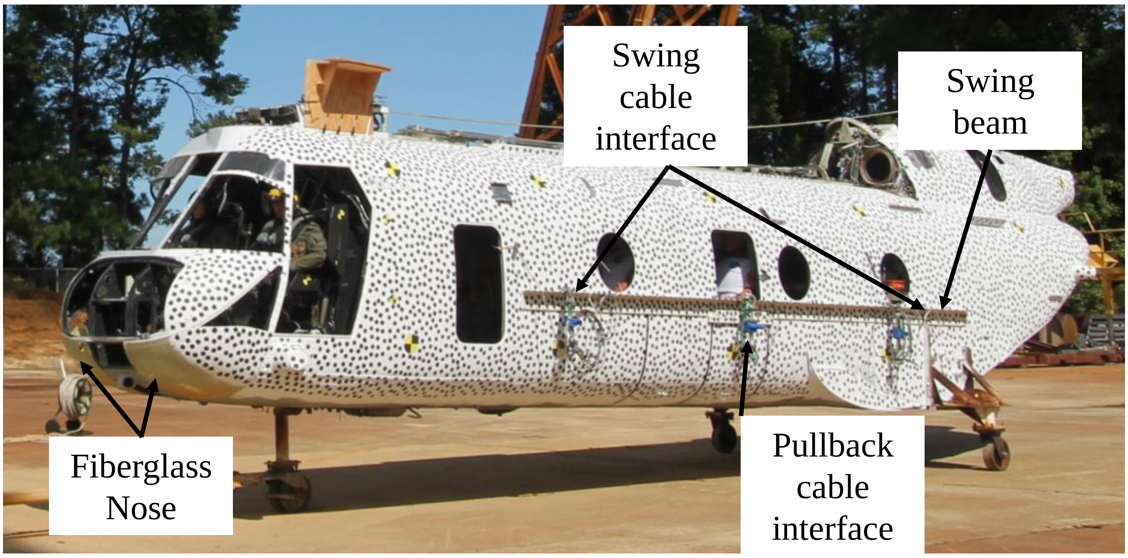


Figure 3. TRACT-Swing Beams and Photogrammetric Dot Pattern

The airframe, seats, restraints, occupants, and ballast were instrumented with accelerometers and load cells. During the test, over 360 channels of data were recorded at 10,000 samples per second using a combination of LandIR, CAMI, and USAARL's ruggedized onboard data acquisition systems (DAS), and 20,000 samples per second using NAVAIR's ruggedized DAS. The distribution of instrumentation included:

- Internal instrumentation of the ATDs, and shoulder or lap belt strap load cells. ATD-specific responses included head, chest, and pelvic accelerations, neck and lumbar forces and moments, chest deflection, and leg rotation.
- Accelerometers that were mounted on blocks at stiff interfaces between frames and skin, or on ballast weight.
- 6 channels for lifting cable load cells.
- An IRIG time code channel for each DAS rack to provide camera and sensor time synchronization.

Video coverage of each test included over 40 high speed and high definition cameras that were mounted onboard and on the perimeter of the test impact location.

Some of these cameras were included to conduct two-dimensional and three-dimensional photogrammetry on the vehicle. The structural response of the airframe was assessed by three-dimensional full-field photogrammetric techniques. All external high speed cameras filmed at 1,000 frames per second, with the exception of the two full-field photogrammetry cameras, which filmed at 500 frames per second. Onboard high speed cameras filming at 500 frames per second were positioned to track ATD motion and the responses of the composite subfloors. Ruggedized high definition cameras filming at 60 or 120 frames per second were also placed throughout the cockpit and cabin. A markerless tracking sensor was mounted within the cockpit bulkhead to track the motion of the standing ATDs.

TRACT EXPERIMENTS

Over eighteen unique experiments were defined for TRACT 1 and TRACT 2. The airframe Fuselage Stations (FS) and locations of each experiment are illustrated in Figure 4. Photos of their locations are shown in Figure 5-8. Detailed descriptions of the experiments can be found in [6] and [7]. Summaries of select experiments are described herein.

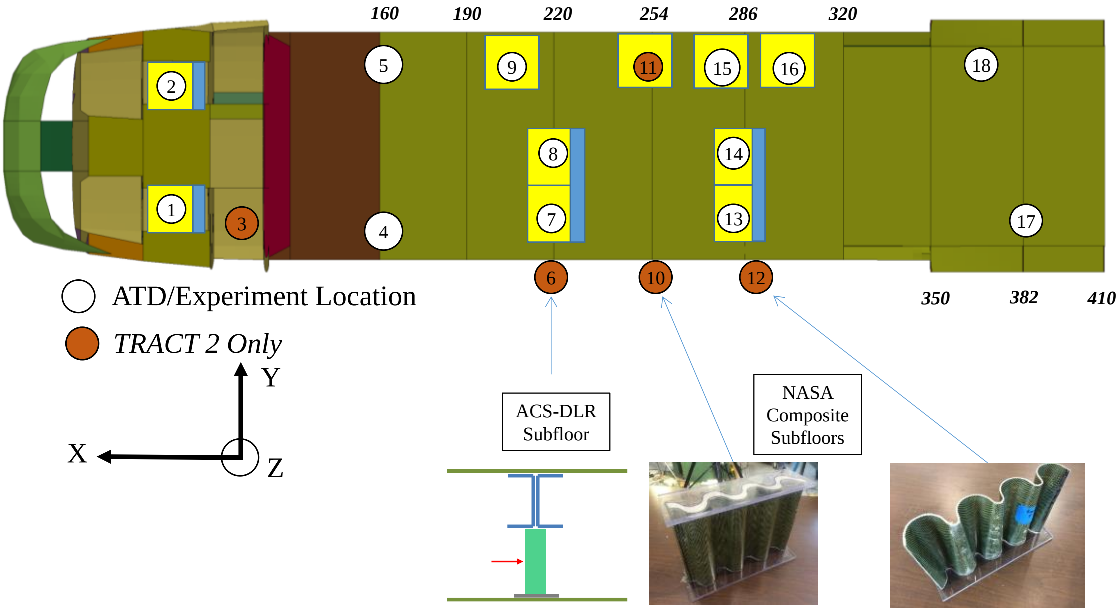


Figure 4. Experiment and ATD Locations- Top View

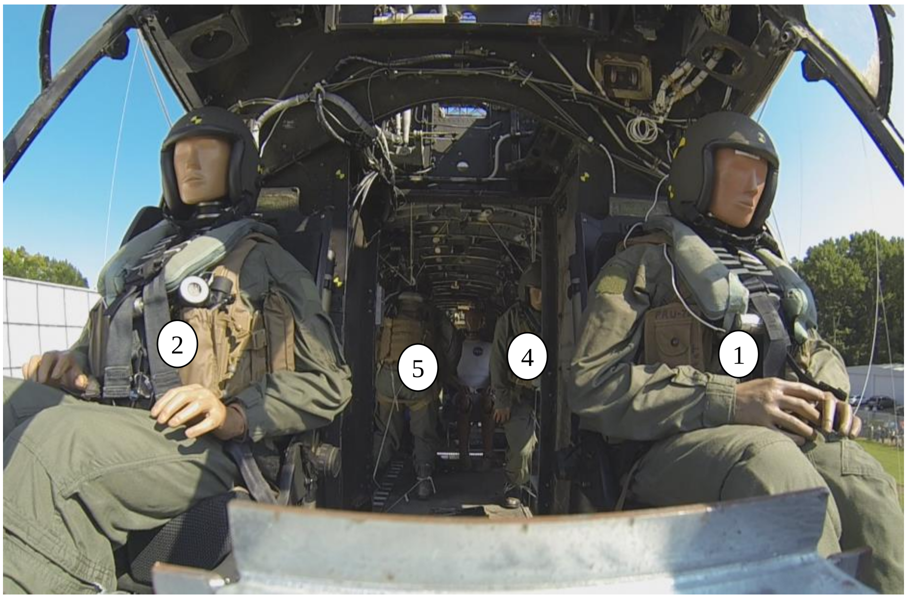


Figure 5. TRACT Experiments- Cockpit and Front Cabin

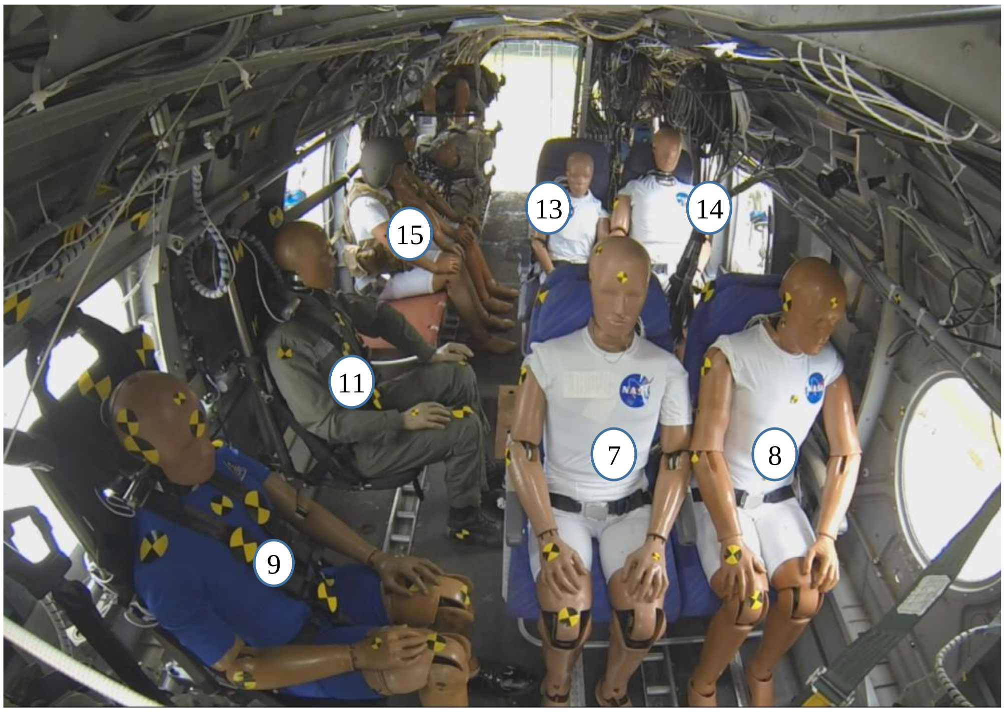


Figure 6. TRACT 1 Experiments- Mid Cabin

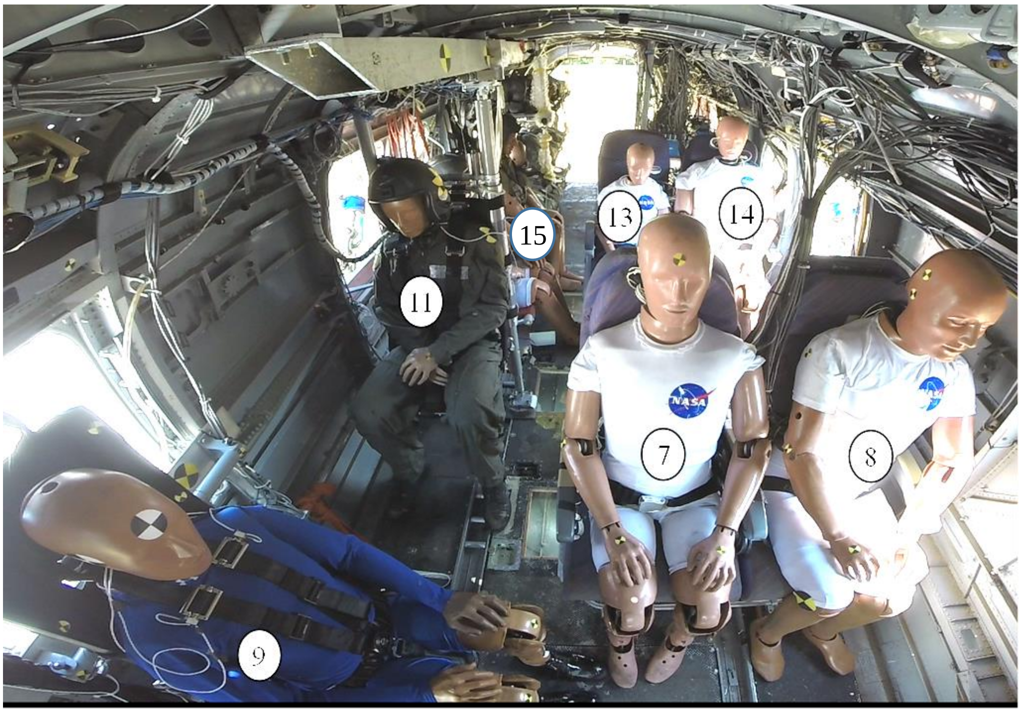


Figure 7. TRACT 2 Experiments- Mid Cabin

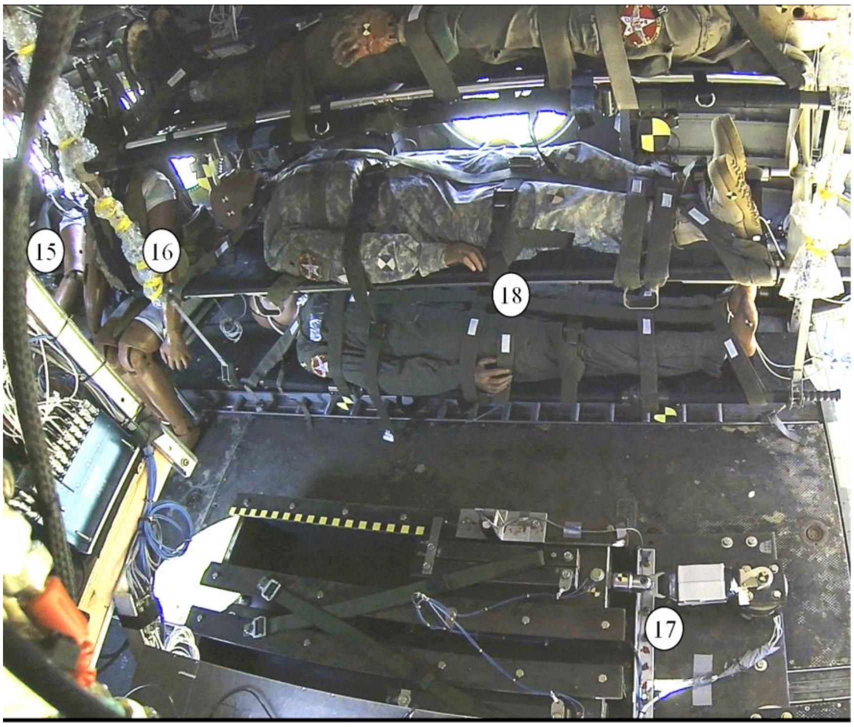


Figure 8. TRACT Experiments- Aft Cabin

The Pre-tensioning Aircrew Restraint System (PARS) system is intended to decrease shoulder belt payout through pyrotechnically actuated spool retraction. Cobham provided the MA-16 inertia reels, the PARS pre-tensioning devices and control modules. The PARS was activated with a crash sensor supplied by BAE Systems and mounted in the cockpit nose. Experiment 1 contained the PARS, while a baseline MA-16 was used for comparison in Experiment 2. Two NAVAIR supplied and fully outfitted 50th-percentile aerospace ATDs were seated in the CH-46E crew seats [8].

The NASA Emergency Locator Transmitter Safety and Reliability (ELTSAR) project is studying the performance of emergency locator transmitters (ELTs) and their insufficient activation rate under severe crash conditions. In TRACT 2, four ELTs were mounted within the cockpit bulkhead (Experiment 3) in various orientations and activation was monitored.

The Mobile Aircrew Restraint System (MARS) was developed by Cobham Mission Systems as a variation on the MA-16 inertia reel [9]. The reel can be mounted along multiple cabin ceiling locations, and extends and retracts the webbing as the aircrew moves about the cabin. In a mishap, the retractor locks and slack is minimized. For TRACT 1, Experiments 4 and 5 contained two NAVAIR 5th percentile pedestrian male ATDs, one attached to a gunner's belt and one with a MARS [10]. For TRACT 2, experiments 4 and 5 contained NAVAIR 5th percentile pedestrian male ATDs in rear and side facing positions attached to MARS [11].

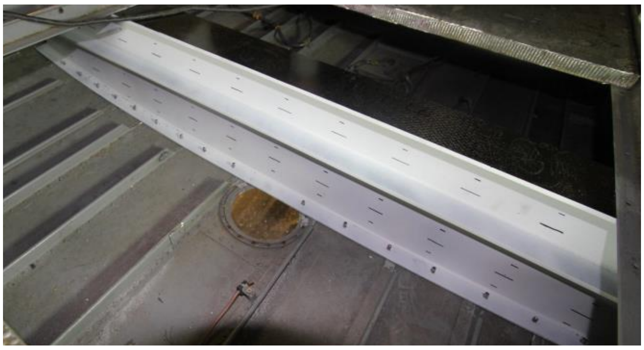
The primary focus for NASA and the RW project was development of retrofit composite airframe concepts. One advantage of the CH-46E cabin is the fact that the frame sections are similar from FS 190 to FS 320. Different corrugated and sine-wave concepts could be installed in place of the aluminum shear webs.

Shear web segments, consisting of carbon and Kevlar woven fabrics, were fabricated and drop tested at LandIR in early 2014. Based on component tests and finite element analyses, two designs were chosen for implementation into the TRACT 2 test. First, a novel "conusoid" section with a hybrid Kevlar/carbon solid laminate molded into alternating cones was developed. Second, a "sinusoid" section, consisting of a wavy sandwich composite with hybrid Kevlar/carbon facesheets and polyisocyanurate foam core, was developed from existing molds fabricated under previous NASA programs. A barrel section removed from TRACT 1 was tested with the two designs installed. Results from the development of the conusoid and sinusoid sections are discussed in [12].

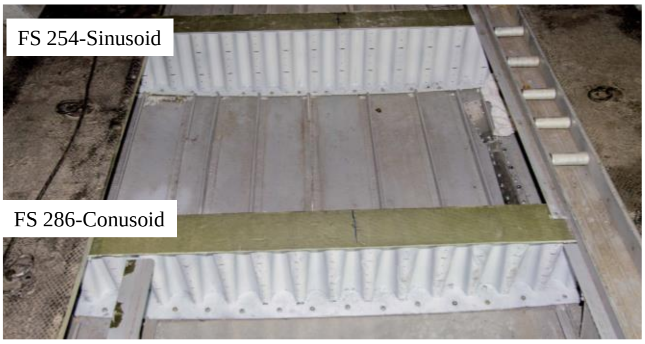
ACS and DLR developed a third composite subfloor made of carbon fiber and containing a stiff upper shear web and a crushable lower web. The ACS-DLR subfloor was installed at FS 220. The two NASA subfloors were installed at FS 254 and 286.

Two pairs of double passenger seats were originally mounted on FS 220 and 286 during TRACT 1. Replacement seats and corresponding ATDs were installed over the ACS-DLR subfloor and the conusoid. A 600-lb ballast mass was mounted over the sinusoid section at FS 254.

The three composite subfloor designs are shown installed within the subfloors of the TRACT 2 test article in Figure 9. The honeycomb sandwich floor sections that cover the composite shear panels were modified to include three polycarbonate windows. High speed cameras were installed just above the three windows to capture video of the impact behavior. The window and floor configuration is shown in Figure 10.



(a) ACS-DLR Composite Subfloor



(b) NASA Composite Subfloors

Figure 9. Composite Subfloor Retrofit for TRACT 2

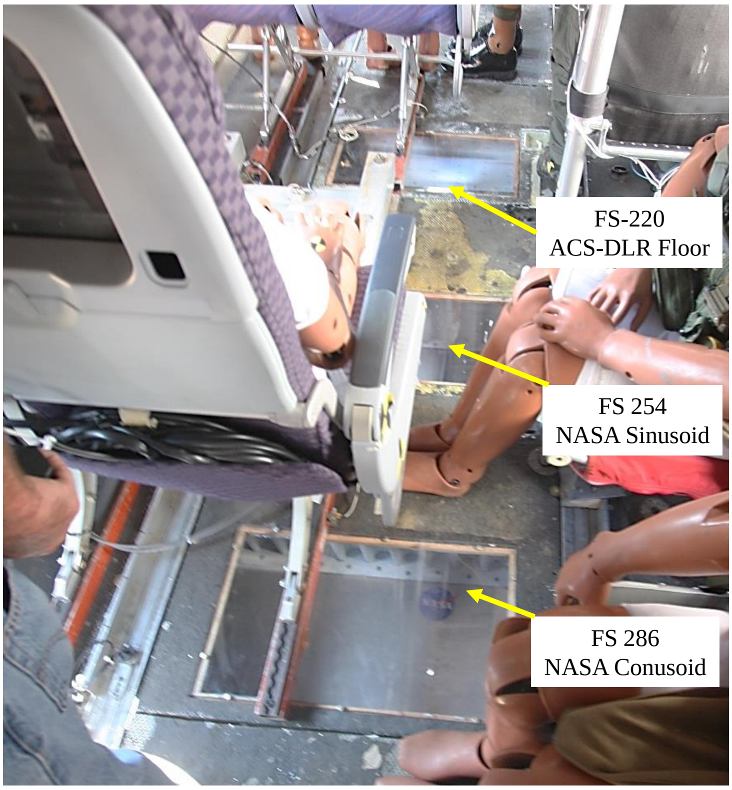


Figure 10. Cabin Installation over Subfloors

The occupant responses in floor mounted cabin seats were tracked with four different ATDs. Two pairs of donated double seats that had been certified to Part 25.562 requirements [13] were used. A 50th percentile Hybrid II (Experiment 7) and 50th percentile FAA Hybrid III (Experiment 8) were seated in the first pair of seats. For TRACT 2, the subfloor was replaced with the ACS-DLR subfloor (Experiment 6). A 95th percentile male (Experiment 14) and a 5th percentile female (Experiment 14) were seated in the second pair of seats. For TRACT 2, the subfloor was replaced with the NASA conusoid floor (Experiment 12). A ballast mass of 600-lb was attached on the shear panel between the two pairs of seats to represent comparable mass loading. For TRACT 2, the subfloor under the ballast mass was replaced with the sinusoid floor (Experiment 10).

The CH-46E Crew Attenuating Crew Seat (CACS) is an energy absorbing foldable seat with a five-point restraint. Two wire bender struts provide vertical load limiting capability for the restrained occupant. CAMI provided a fully instrumented FAA 50th-percentile Hybrid III ATD with an ES-2re head and neck for use on a side facing CACS seat (Experiment 9). The ES-2re head and neck components provide more biofidelic head/neck kinematics in the lateral direction and injury criteria are available to relate the measured neck loads to injury risk [14]. For TRACT 1, the FAA ATD was compared with a side-facing NAVAIR 50th-percentile Aerospace Hybrid III in a CACS seat. That seat was replaced in TRACT 2 by an energy absorbing troop seat developed by Safe, Inc. and evaluated by NAVAIR. The seat is attached to two telescoping vertical tubes using selectable profile energy absorbers [15]. The vertical tubes are bolted to the floor and ceiling (Experiment 11). Since the CH-46E cabin does not support significant overhead mass, the cabin ceiling was highly reinforced to allow seat loads to transmit without excessive deformation. NAVAIR supplied a 50th-percentile aerospace ATD for this seat.

CARGO PMO is evaluating a new side-facing troop seat for the CH-47 program known as the Crash Resistant Troop Seat (CRTS). For TRACT 1, a legacy CH-46E troop bench, which is an aluminum seat pan frame with canvas mesh overwrap and lap restraints, was used. For TRACT 2, CARGO PMO supplied a standard 1-man 8-g troop bench seat (Experiment 15) and the CRTS (Experiment 16). NASA provided two 50th-percentile Hybrid II ATDs.

A load-limiting cargo restraint was developed by NAVAIR and Pennsylvania State University that uses a stitch ripping device (SRD) [16]. Energy is absorbed by webbing extension, thread rupture and stitch slippage. One 500-lb sliding mass was connected to an SRD and another 500-lb mass was connected to a standard webbing restraint with forces measured by end line load cells (Experiment 17).

USAARL is investigating crash performance issues related to patient litter systems located in the cabin of a rotary wing airframe. Legacy litter systems in military rotorcraft are qualified under static loading, and standards have not been updated in the same manner as have crashworthy seats. USAARL provided a triple litter, litter stanchions compatible with the CH-46E, a single instrumented ATD, and a non-instrumented ATD. NAVAIR provided two non-instrumented ATDs (Experiment 18).

The target impact velocities were 25-ft/sec vertical and 33-ft/sec horizontal. This impact condition represented a severe, but potentially survivable impact scenario approaching the civilian 95th-percentile impact envelopes, but lower than the military envelope. The structural capability of the CH-46E, which is a legacy airframe not designed to the military standard for crashworthiness [4], was also taken into consideration. It was desirable to achieve nearly uniform loading across the cabin while preventing a nose-down condition that would overload the cockpit disproportionately. Typical pitch deviations from nominal in previous LandIR tests with the four swing cable configuration were ± 2-degrees. Therefore, a pitch-up angle of 2-degrees was chosen, and the actual pitch-up angle was 2.5-degrees.

A recent mishap study for military rotorcraft [17] indicated that nearly 70% of crashes occur on non-prepared surfaces. Crashes onto sod also have a lower survivability rate than crashes onto prepared surfaces. Based on this finding, a mixture of clay and sand that had previously been used for Orion crew module testing was used as the impact surface [18].

TRACT 1 RESULTS

The TRACT 1 test was conducted on 28 August 2013. The vertical and horizontal impact velocities were 25.0- and 33.0-ft/sec, respectively. Figure 11 shows the front view of TRACT 1 prior to impact. The airframe impacted the soft soil with a 2.5-degree nose-up pitch attitude, and less than 1.0-degree yaw to the right. Only airframe accelerations/loads will be reported. Information on particular experimental results can be found in [8] and [10].

Figure 11. TRACT 1 Front View, Prior to Impact

The photogrammetry results were first used to examine the airframe deformation and performance. Photographs of the impact sequence for TRACT 1 with full-field photogrammetry of the lateral deformation are shown in Figure 12. The 2.5-degree pitch up caused the aft frames to impact initially. The airframe rotated about these rear frames allowing the forward cabin to impact the soil after approximately 0.020-seconds after initial impact. At 0.1-seconds, the helicopter rebounded slightly, while maintaining a slight nose-down pitch and rolling towards the starboard side. A smaller secondary impact occurred at 0.55-seconds, and the test article came to rest at 0.9-seconds. The forward slide out of the test article was measure to be 96-inches. In Figure 12, the lateral deformations are clearly visible just at window height, indicating dilation of the airframe as the understructure impacts.

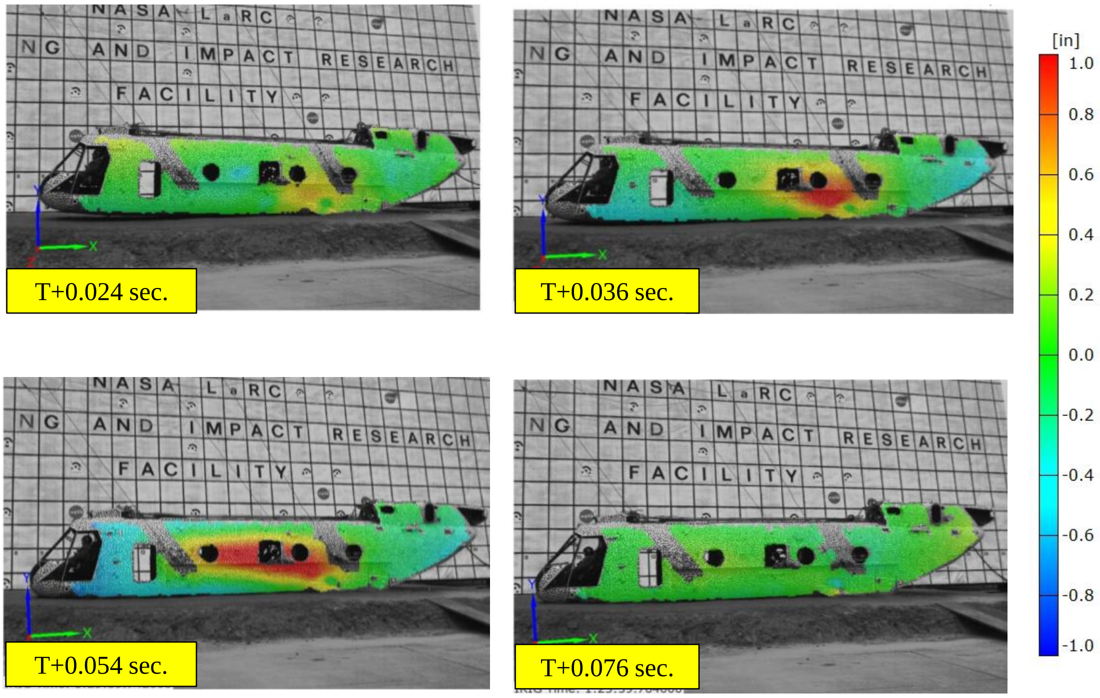


Figure 12. TRACT 1 Impact Sequence and Lateral Displacement from Photogrammetry

A schematic of the fuselage highlighting airframe FS locations is shown in Figure 13. All accelerations are low-pass filtered to the SAE J211 standard, using a Channel Frequency Class (CFC) 60 [19] for vehicle accelerations. FS 410 is located at the aft cabin/tail splice frame, FS 254 is located at mid-cabin, and FS 152 is located at the cockpit/forward cabin splice frame. The pilot and co-pilot responses are recorded on the floor supporting the seat rails.

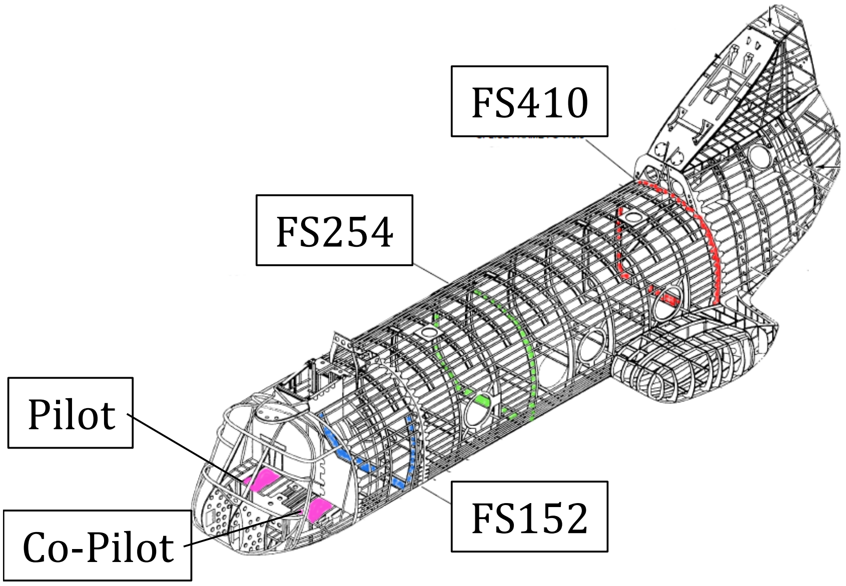


Figure 13. Schematic of Helicopter Showing Instrumentation Locations

Given the nose-up pitch attitude at impact, it is expected that the onset of acceleration would occur first for FS 410, next for FS 254, and last from FS 152. The data shown in Figure 14 confirm this. The left side acceleration responses range in peak magnitude between 25- and 45-g with durations of approximately 0.08 seconds. The right side responses range in peak magnitude between 22- and 55-g with a duration of approximately 0.08 seconds. At FS 152, there is a noticeable negative component of acceleration before 0.03 seconds as the test article pitches down. The behavior is more pronounced in the pilot and co-pilot responses. The co-pilot and pilot responses have very high magnitude oscillations after slam down at 0.04 seconds. There is a large difference between the co-pilot and the pilot responses because of the locations of the accelerometer blocks on the thin-walled floor.

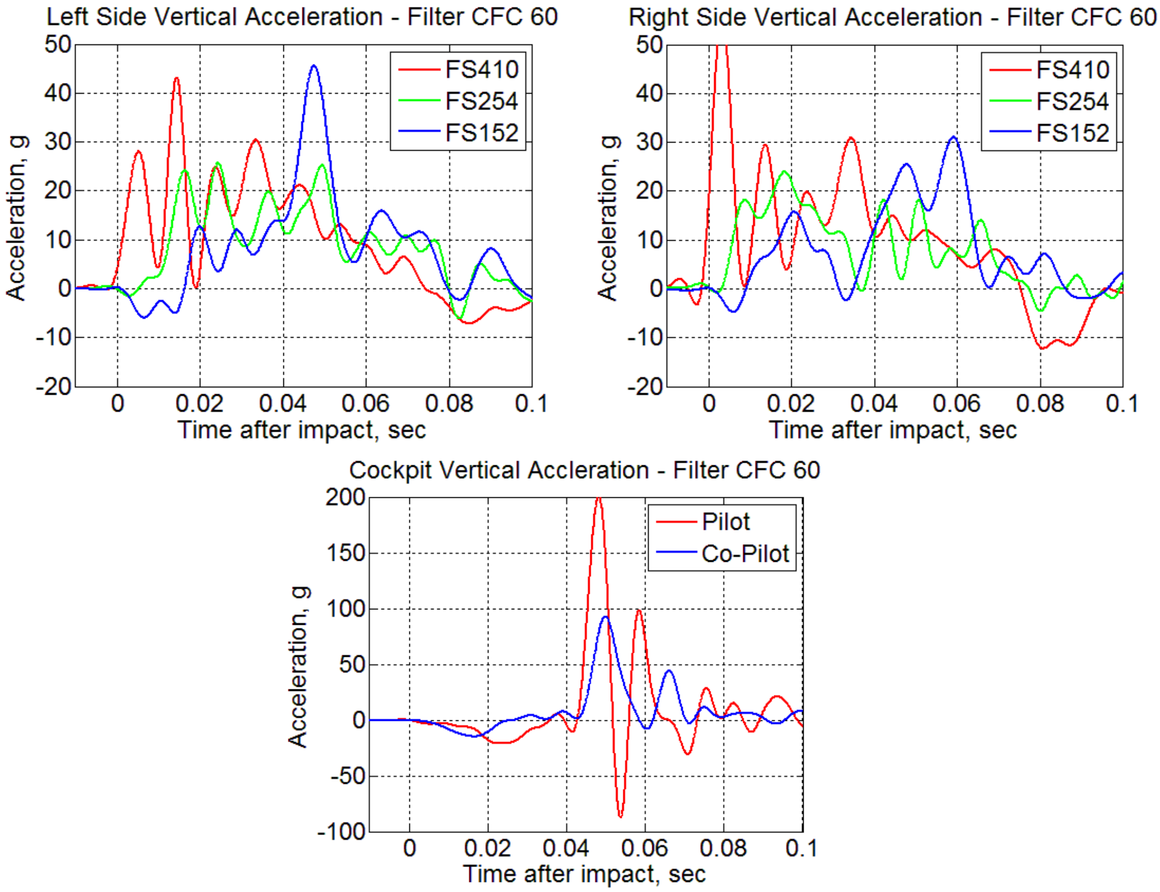


Figure 14. Vertical Floor-Level Acceleration Results for the Left and Right Sides of the Cabin and the Cockpit

Horizontal acceleration time history responses are shown in Figure 15, along with a fuselage schematic showing instrumentation locations. Three plots are shown for the left and right sides of the airframe, and for the cockpit. Each of the curves shows a similar response, with average magnitudes of approximately 10-g. The entire aircraft begins to horizontally decelerate within the first 0.005 seconds. The magnitude of the peak horizontal acceleration is approximately 30-g; however, most traces are lower.

The orientations and magnitudes of the resultant accelerations just before and after cockpit belly impact are illustrated in Figure 16. In Figure 16a, the orientation of the airframe deceleration is pointed to the aft and down. The pilot and co-pilot excursions are in the opposite direction, upward and forward. The magnitude of the negative component is approximately 10-g during nose over. In Figure 16b, after cockpit belly impact, the acceleration is directed up and slightly aft with a magnitude greater than 95-g.

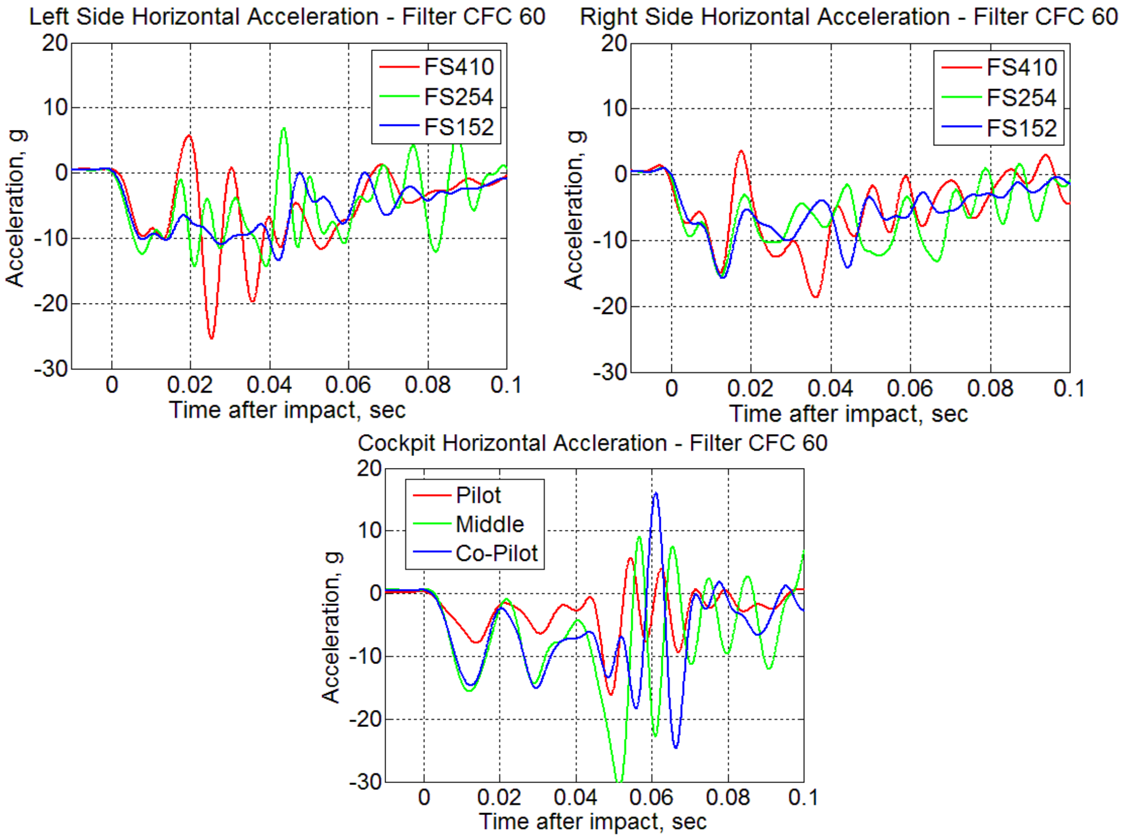


Figure 15. Horizontal floor-level acceleration responses

a) Before Impact

b) After Impact

Figure 16. Cockpit resultant acceleration

Cabin mid-wall and floor vertical acceleration responses are shown in Figure 17, along with photographs indicating the locations of instrumentation. The mid-wall traces indicate two peaks, the first having a magnitude of approximately 20-g and the second having a magnitude of 25-g. The floor traces are from the two pair of forward facing seats. Whereas the mid-wall traces were very similar, the floor traces are opposite to one another. The forward seat exhibits a 15-g uniform acceleration response, which suddenly increases near the end of the pulse to a peak of 38-g. Conversely, the rear seat exhibits an initial peak of 34-g, which is reduced to a relatively uniform 15-g response that decays near the end of the pulse. Both responses have durations of approximately 0.08 seconds.

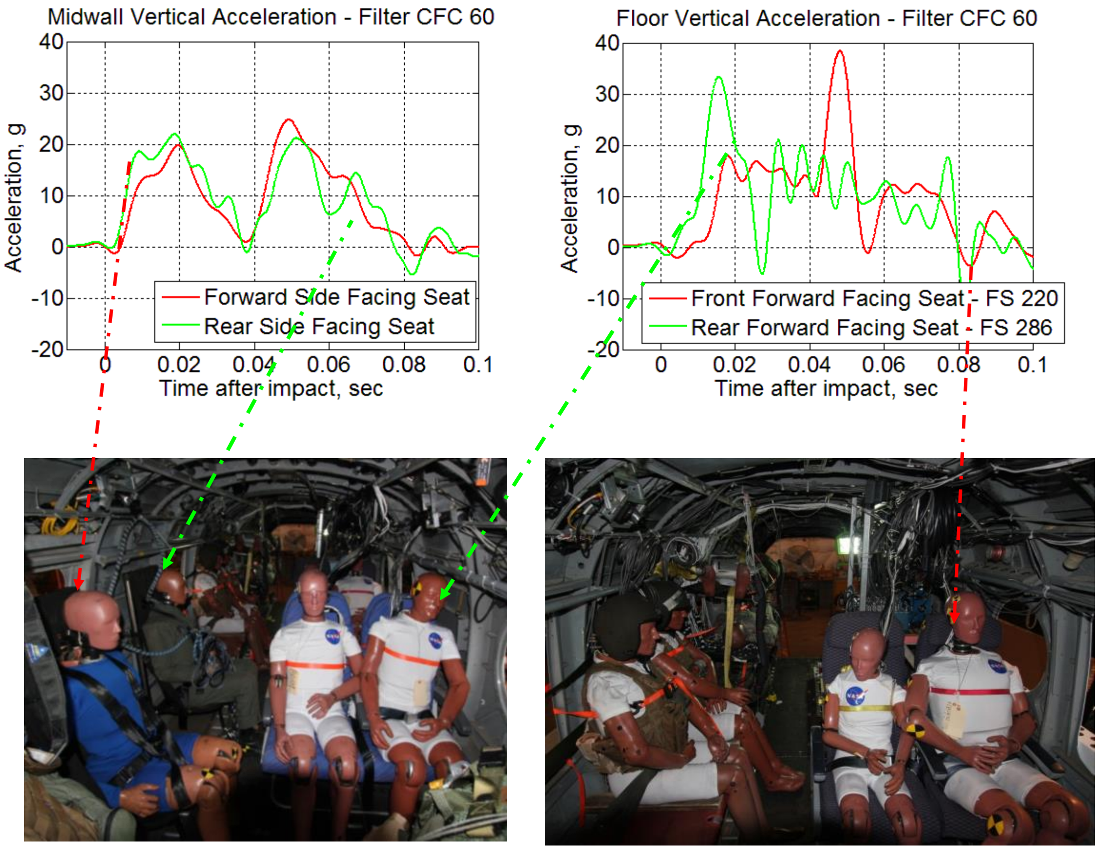


Figure 17. Cabin vertical acceleration responses at seat attachment locations

TRACT 2 RESULTS

The TRACT 2 test was conducted on 1 October 2014. Figure 18 shows the TRACT 2 orientation just prior to impact. The vertical and horizontal impact velocities were 25.4- and 33.7-ft/sec, respectively. The airframe impacted the soft soil with a 2.5-degree nose-up pitch attitude, and a 3.6 degree roll to the left, and a 2.5-degree yaw to the right. The aft left side impacted initially. The roll and yaw angles were significantly higher than TRACT 1. A time lapse photo sequence from an external high-speed camera is shown in Figure 19. The region forward of the stub wing box begins to crush 0.016-seconds after impact. Cockpit touchdown occurs at 0.045-seconds. At 0.055-seconds, the subfloor skin between FS 190 and FS 220 begins to dimple inwards. The aft cabin and tail rebounded starting at 0.090-seconds, and reached maximum rebound height at 0.280-seconds. This rebound height was about 30% lower than the rebound height seen in TRACT 1. Following the second contact of the cabin belly on the soil, the test article came to rest abruptly at 0.53-seconds.

Figure 18. TRACT 2, Front View, Prior to Impact

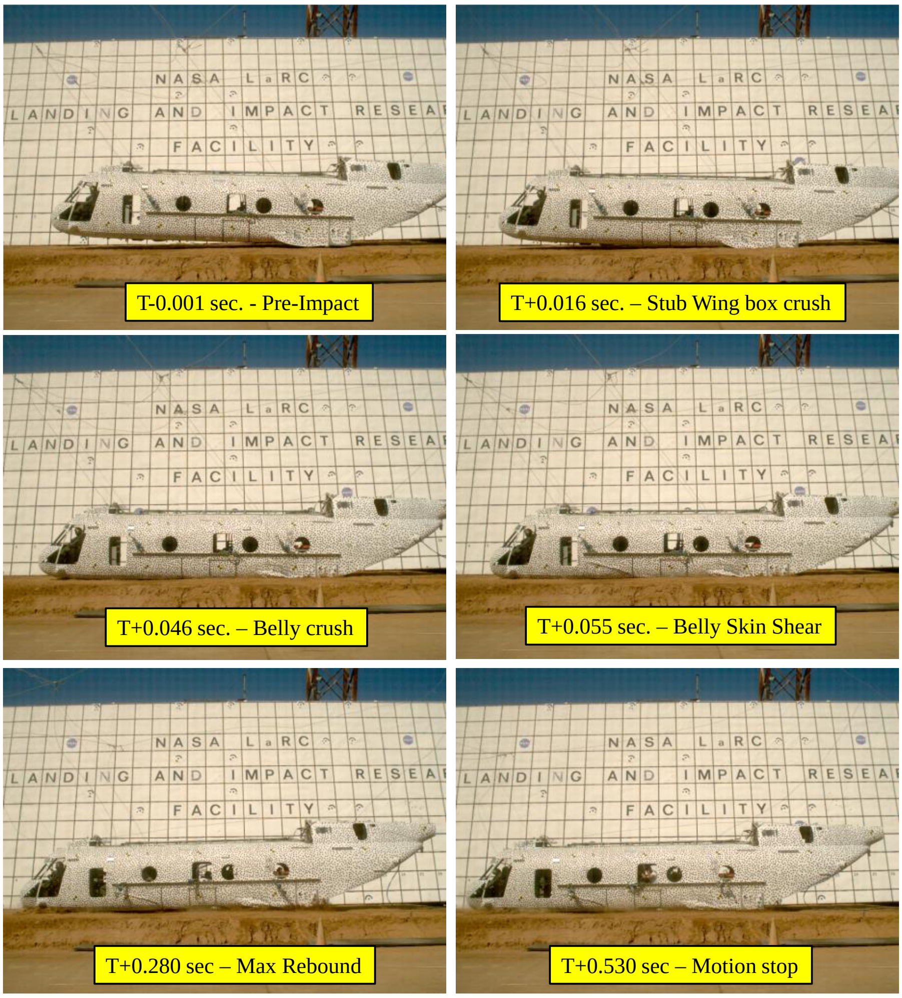


Figure 19. Impact sequence of TRACT 2 test

The total slide out distance was 51-inches, slightly more than half that of TRACT 1 (96-inches). At first glance, there did not appear to be any differences in the soil characteristics compared to TRACT 1. Measurements taken with a hemispherical penetrometer, which produces craters that are measured on the order of several inches, showed similar behavior to soil measurements taken during TRACT 1. However, the soil properties were further studied with a dynamic cone penetrometer (DCP), which samples the bearing strength of the soil at various depths. At around 10 inches of depth, the soil softens considerably due to high moisture content, ranging from 9.7% to 16%. A representative plot of the California Bearing Ratio (CBR) versus depth is shown in Figure 20. The layered soil with a softer base yielded a large crater depth, as deep as 9-inches.

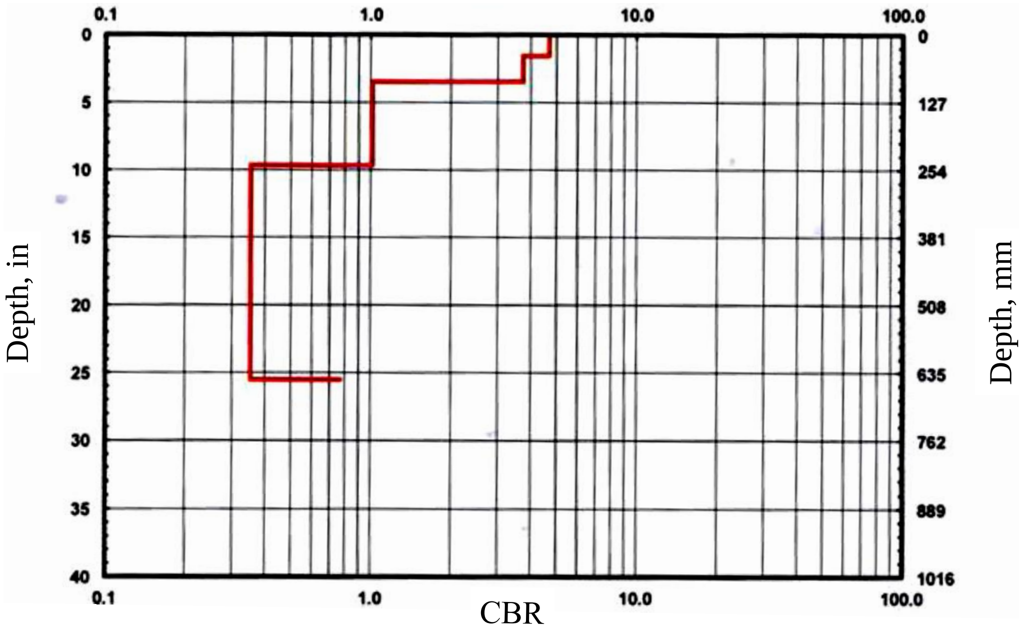


Figure 20. TRACT 2 Soil Strength

Figure 21 shows a plot of the horizontal velocities for the airframe at the horizontal CG for both TRACT 1 and TRACT 2. The velocities were computed using photogrammetry, and the points that were tracked are shown in the photograph of Figure 21. For TRACT 1, the airframe lost only 20-ft/sec of horizontal velocity at 0.1-seconds at which point the airframe rebounded off the soil. TRACT 2 shows an almost 30-ft/sec reduction in horizontal velocity since the airframe did not completely rebound off the soil. The time to rest was half that of TRACT 1 (0.53-seconds versus 0.9-seconds).

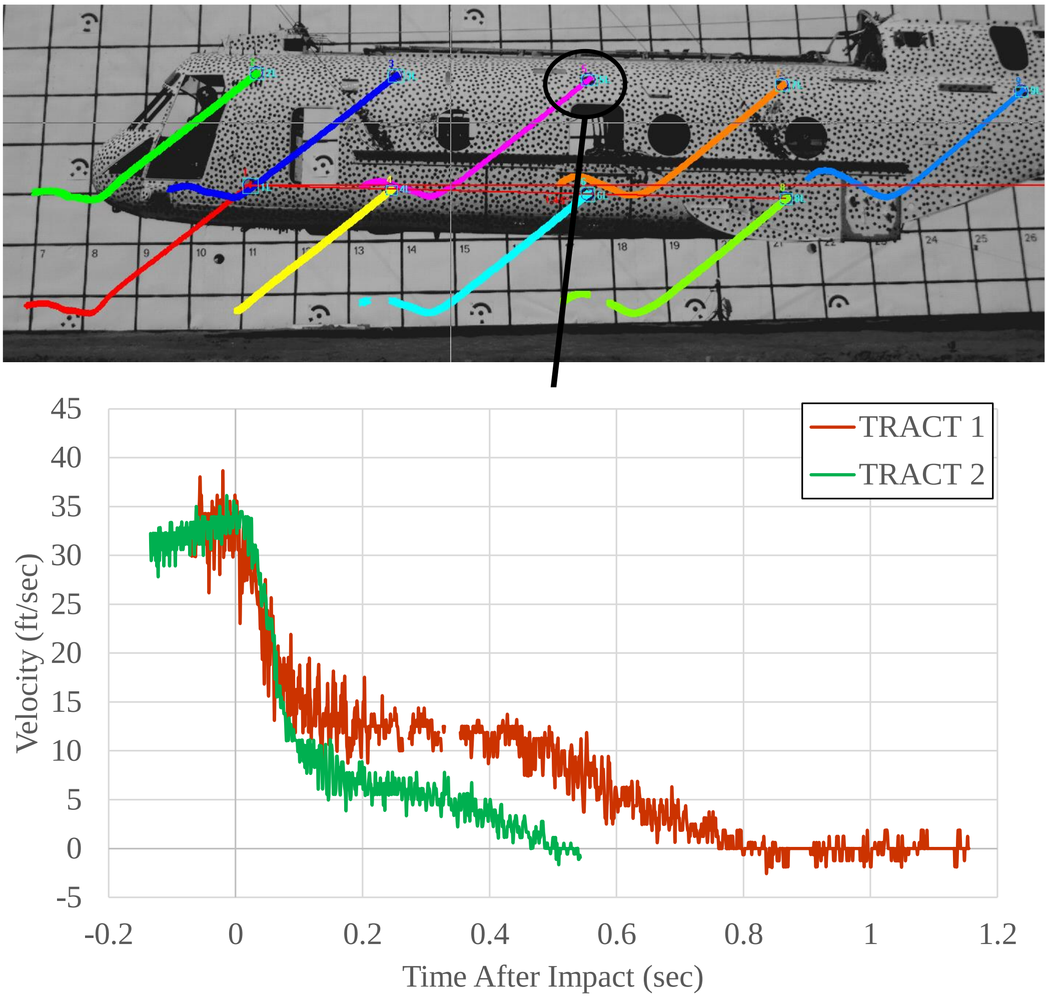


Figure 21. Comparison of TRACT 1 and TRACT 2 Horizontal Velocities

Full-field lateral displacements of the outer surface of the sidewall skin are fringe plotted in Figure 22. The peak displacements in and out of the page are represented by dark blue and red colors, respectively. The baseline reference state is shown at 0.010-seconds before impact. At 0.025-seconds after impact, the skin aft of FS 286 begins to bow out. Meanwhile, the cockpit skin displaces inwards, because the cockpit is rolling from left to right. At 0.043-seconds, the cockpit belly impacts, and the skin above the cockpit belly deforms outward.

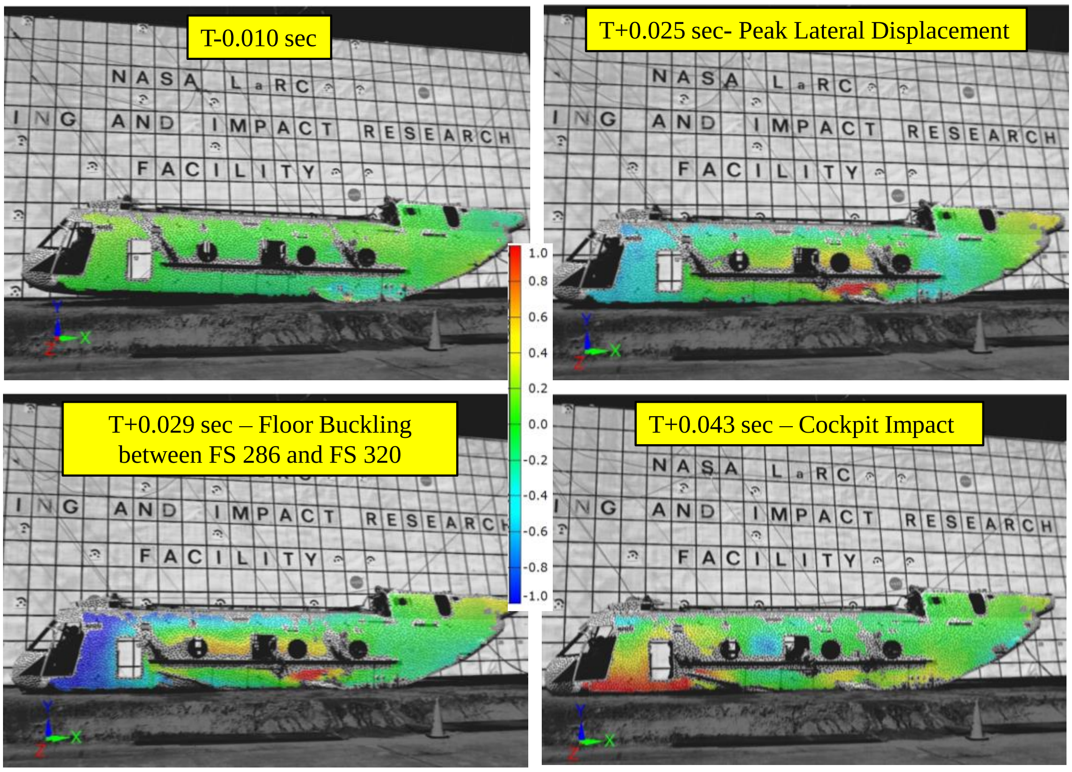


Figure 22. TRACT 2 Lateral Displacement from Photogrammetry

The region in the aft section of the cabin was expected to sustain high vertical accelerations with the initial impact occurring on the aft left side. Figure 23 shows the vertical accelerations at FS 410 near the floor. The left side of FS 410 was the location of the NAVAIR/Penn State cargo restraint experiment and the right side of FS 410 was where the USAARL patient litter experiment was located. The vertical acceleration at FS 410 (L) is a sustained 20-g load over 0.050-seconds, while FS 410 (R) shows a peak of 41-g occurring at 0.025-seconds after impact as the airframe rolled right. The crushing behavior of the left side of the aft cabin was comparable to an energy absorber.

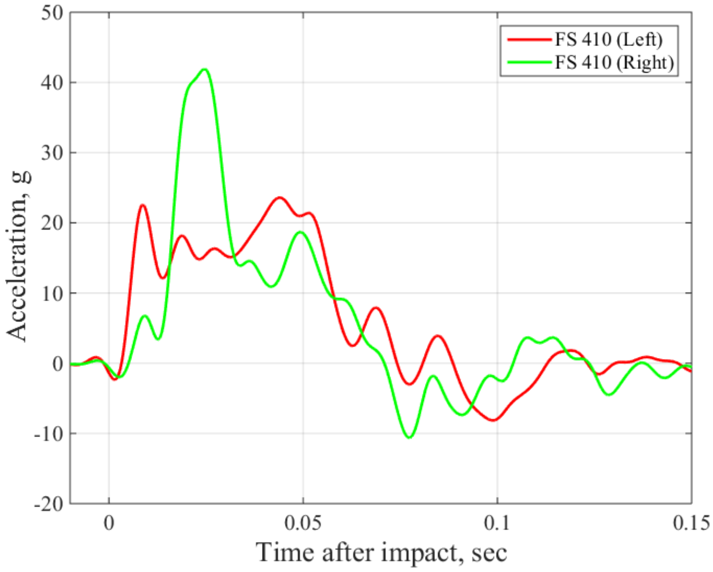


Figure 23. TRACT 2 Aft Cabin Frame Vertical Accelerations- Adjacent to Floor

A photo of the understructure after impact is shown in Figure 24. Significant deformation is seen in the tail, and the belly skin is torn at FS 220, 254, and 286. The progression of failure is evident when viewing an onboard time lapse of the three critical frame sections, shown in Figure 25. At 0.010-seconds, the 5th and 95th percentile NASA ATDs press into the seat cushions. At 0.046-seconds, the belly skin begins to dimple up aft of the flange of the conusoid. All three subfloors begin to fold as the floor moves forward relative to the belly. The belly and subfloor sections then can no longer support any of the horizontal loading. At 0.1-seconds, the ATDs flail forward, and the induced loads and moments from the ATDs cause the floor above the conusoid and ACS-DLR to detach. This response differed from TRACT 1, where only minor horizontal shearing was evident in the cabin subfloors.

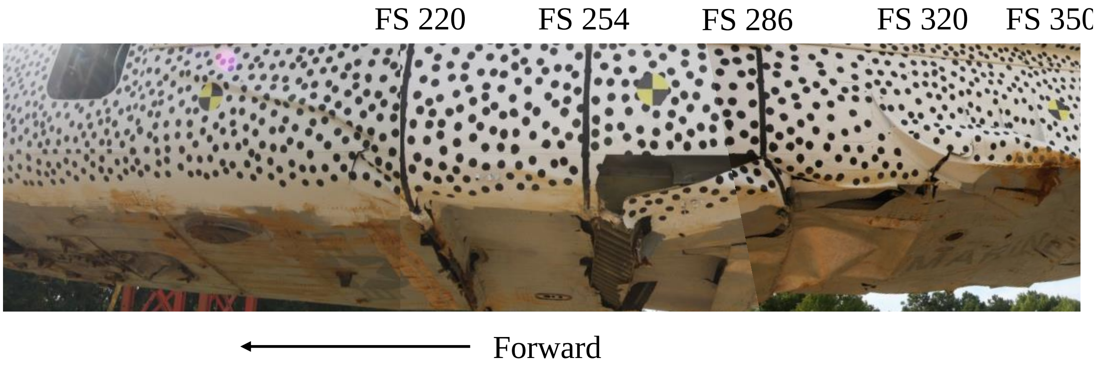


Figure 24. TRACT 2, Post-test Photo, Airframe Deformation

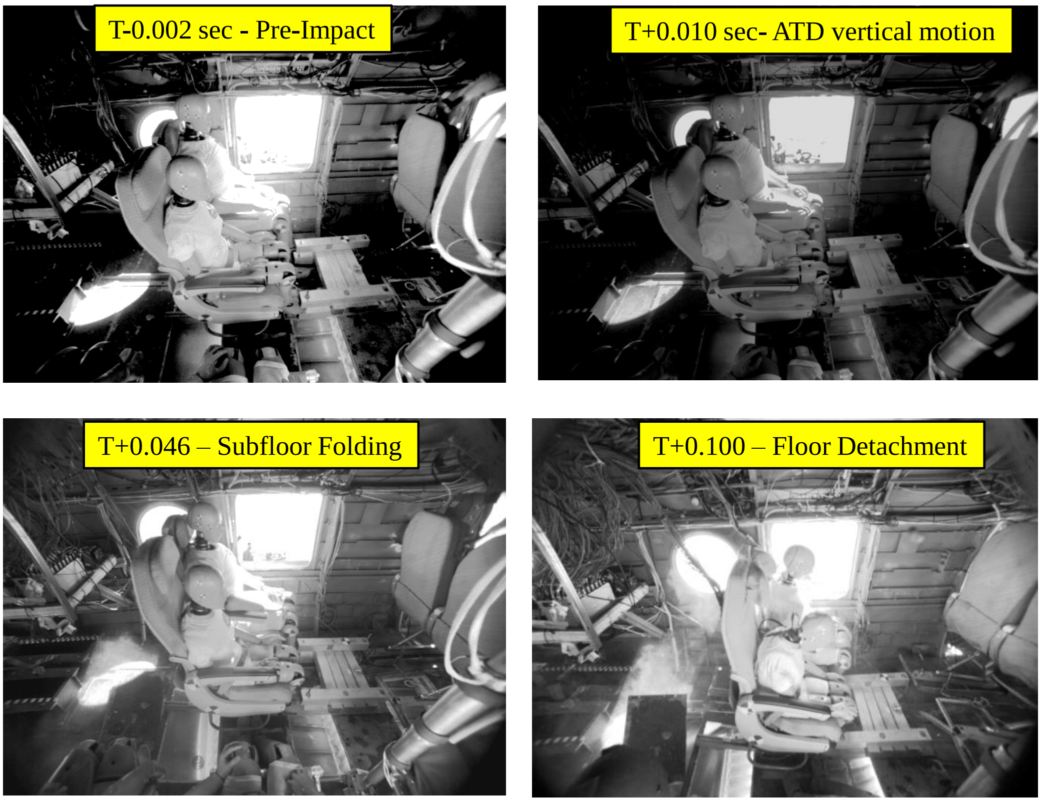


Figure 25. TRACT 2 Cabin, Impact Sequence

All accelerations are low-pass filtered to the SAE J211 standard, using a Channel Frequency Class (CFC) 60 [19] for vehicle accelerations. Vertical acceleration plots near the cabin floor centerline reveal the lack of subfloor energy absorption and load transfer seen in TRACT 1. Figure 26 shows the vertical accelerations above the ACS-DLR subfloor and the conusoid. Peak accelerations are 70-g at the conusoid and 55-g at the ACS-DLR subfloor and the durations are approximately 0.015-seconds. By contrast, the TRACT 1 accelerations were less than 40-g.

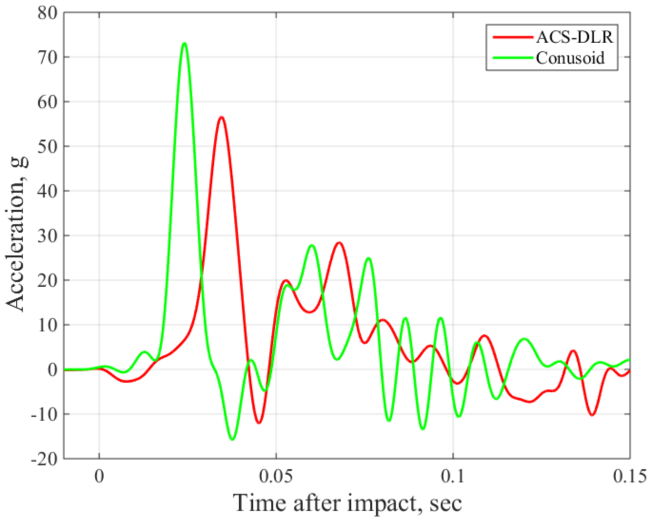
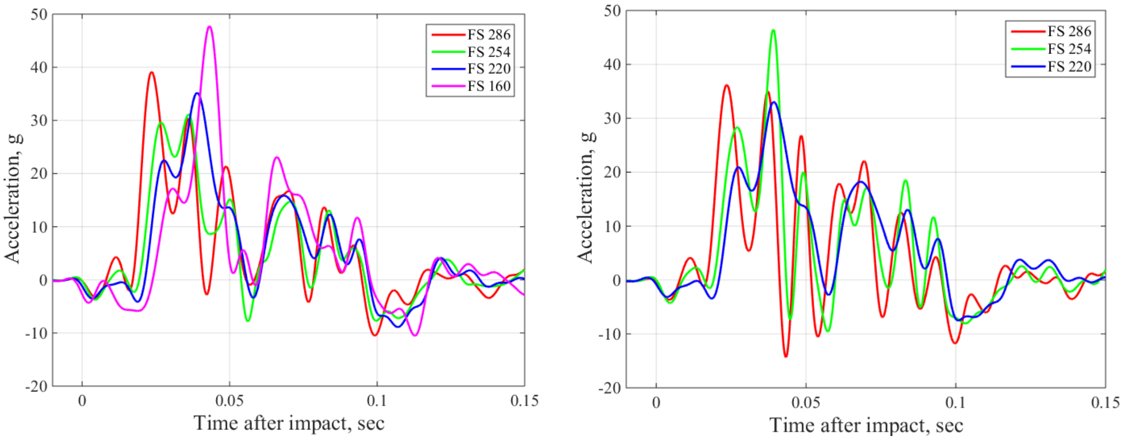


Figure 26. TRACT 2 Mid-Cabin Floor Vertical Accelerations

The vertical responses from accelerometers mounted on cabin frames are plotted in Figure 27. Figure 27(a) shows the vertical accelerations on the frames at floor-height. Figure 27(b) shows the vertical accelerations on the frames at window height. The acceleration profiles are similar to TRACT 1, ranging from 20-g to 40-g and a duration of 0.080-seconds. As the airframe pitches over from initial contact, there is a negative component of acceleration which is amplified going forward in the cabin. This negative component is evident in the acceleration response of FS 160 at approximately 0.020-seconds, as shown in Figure 27.



a) Frame adjacent to floor

b) Sidewall

Figure 27. TRACT 2 Mid-Cabin Frame Vertical Accelerations

The horizontal accelerations as recorded by accelerometers mounted on cabin frames are plotted in Figure 28. The acceleration traces are similar to TRACT 1 in duration, but the magnitudes range from 15-g to 30-g for TRACT 2 which is higher than the 10-g average peak for TRACT 1.

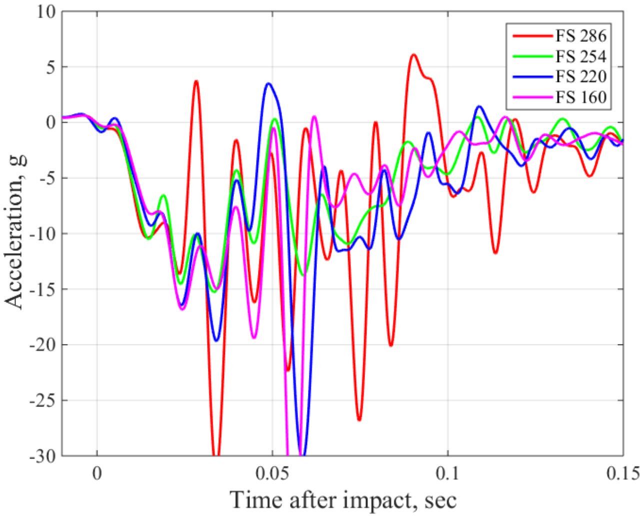
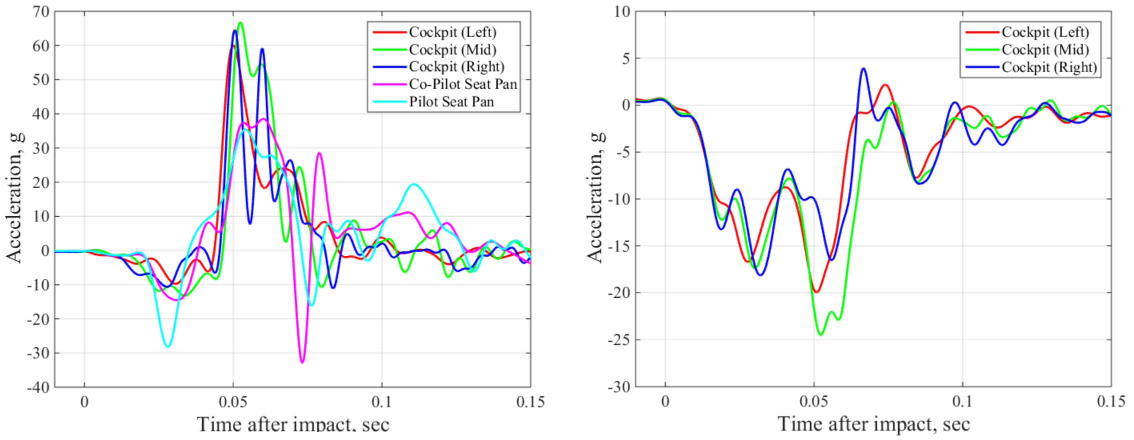


Figure 28. TRACT 2 Cabin Frame Horizontal Accelerations- Adjacent to Floor

The vertical accelerations on the cockpit floor under the pilot and co-pilot seats, within the center console, and on the seat pans are shown in Figure 29(a). The negative accelerations due to the airframe pitching over are greater than 10-g. The peak loads on the floor are 60-g to 70-g with a duration of 0.050-seconds. The energy absorbing seats attenuate the loads, with seat pan loads peaking around 35-g.

The horizontal cockpit accelerations on the cockpit floor under the pilot and co-pilot seats and within the center console are plotted in Figure 29(b). The accelerations are consistent with the rest of the airframe with peaks of 15-g to 20-g and durations of 0.100-seconds



a) Vertical (CFC 60)

b) Horizontal (CFC 60)

Figure 29. TRACT 2 Cockpit Accelerations- Cockpit

CONCLUSION

The Transport Rotorcraft Airframe Crash Testbed (TRACT) full-scale crash tests of a CH-46E helicopter airframes were conducted in 2013 and 2014 at the LandIR facility. The impact test conditions were considered lower than typical DOD qualification levels, but severe enough to approach civilian survivability envelopes. The primary difference between the TRACT 1 and TRACT 2 test article was the inclusion of three composite retrofit subfloors. The TRACT 2 test provided additional data to assess crashworthy systems performances. Several modifications to experiments in TRACT 1 were made for TRACT 2, based on the results of TRACT 1.

Over 360 channels of airframe and Anthropomorphic Test Device (ATD) data were collected with less than 5% loss of signal. External and onboard high speed and high definition cameras numbering more than 40 cameras provided for coverage. Numerous experiments were conducted as part of the crash test. These experiments included:

- Comparison of ATD responses in a CH-46 crew seat with MA-16 inertia reel versus a CH-46 crew seat with PARS
- Comparison of floor-mounted passenger seat and ATD responses

- Comparison of standing ATDs with an Aircrew Endurance Vest and a Mobile Aircrew Restraint System (MARS)
- Full-field three-dimensional photogrammetry data collection
- A Hybrid III ATD with ES-2re head and neck, on a sidewall-mounted Crash Attenuating Crew Seat (CACS)
- Comparison of the sidewall mounted Crash Resistant Troop Seat (CRTS) with a single CH-47 tube and rag sidewall troop seat
- Comparison of cargo experiment with non-energy-absorbing restrained cargo mass and energy absorbing restrained cargo mass
- Three-tiered litter with reinforced litter stanchions
- Emergency Locator Transmitter performance

The vehicle slide out distance of TRACT 2 was nearly half that of TRACT 1. The horizontal accelerations were 50% higher for TRACT 2 than TRACT 1, due to a combination of factors. One factor was higher soil moisture, causing a reduction in stiffness and increased soil cratering. In addition, modifications to the cabin floor, subfloor, and belly skin destabilized the structure. Extensive damage occurred to the understructure near the composite subfloors, and the subfloors sheared horizontally before they could undergo stable crushing. More horizontal rigidity is required to hold the subfloor sections upright during impact.

The vertical decelerations within the cabin were similar to TRACT 1 and varied from 20- to 50-g. The 2.5-degree pitch up attitude caused the cockpit to accelerate downward just prior to belly contact. Vertical seat pan accelerations exceeded 60-g due to the weaker cockpit structure.

The TRACT 1 and TRACT 2 tests proved to be a highly beneficial collaboration between the FAA, DOD, and industry. The opportunity to assess full-scale crashworthiness under combined horizontal and vertical impact conditions is uncommon. TRACT 1 and TRACT 2 demonstrated that this range of testing was both economically and technically feasible.

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