

Evaluation of the Second Transport Rotorcraft Airframe Crash Testbed (TRACT 2) Full Scale Crash Test

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ABSTRACT

Two 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 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 Anthropomorphic Test Devices (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 longitudinal 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

There is a reluctance to conduct full-scale crash safety tests by civil and military rotorcraft manufacturers due to perceived constraints such as cost-effectiveness and asset allocation. In those instances where there have been dedicated test articles for destructive testing, tests have been conducted by suspending the article from a release hook or a guided rail.

Crash tests are usually conducted under severe, but survivable conditions. For civilian rotorcraft, the 95th-percentile survivable impact velocities were determined from mishap data as 26-ft/sec vertical and 50-ft/sec longitudinal (Ref. 1). There are no specific impact condition requirements for civilian rotorcraft. However, 95th percentile combined envelopes are derived based on the vertical and longitudinal bounds. Compared to civilian data, military 95th-percentile velocities are higher in the vertical (42-ft/sec) and similar in the longitudinal directions. A set of impact condition guidelines have been defined for military rotorcraft (Ref. 2). One case includes significant components of velocity in both

the longitudinal (27-ft/sec) and vertical (42 ft/sec) directions. It is therefore important to consider the coupled response of the airframe and the occupants to impacts containing significant components of both longitudinal and vertical velocity.

Drop test articles can be oriented to introduce vertical velocities as well as lesser components of longitudinal 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 longitudinal and vertical velocities. However, horizontal velocity is limited by the rail length, which determines 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

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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.



Figure 1. Landing and Impact Research Facility

TRACT 1 BACKGROUND

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

- 1) Evaluate the integrated airframe, seat, and occupant response under a combined horizontal and vertical impact velocity.
- 2) Assess improvements to occupant loads and flail envelope with the use of crashworthy features such as

pre-tensioning active restraints and energy absorbing seats.

- 3) Provide data for comparison to finite element analyses.
- 4) Evaluate the response of composite energy attenuating subfloors under severe but survivable conditions.
- 5) Evaluate advanced biofidelic ATDs such as the ES-2re.
- 6) Develop novel techniques for photogrammetric data acquisition to measure occupant and airframe motion.

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. A photograph of one of the CH-46E airframes is shown in Figure 2.



Figure 2. CH-46E Airframe

Requests for participation were circulated with the Federal Aviation Administration (FAA), Department of Defense (DOD), and rotorcraft industry manufacturers. The first crash test (TRACT 1) was conducted in August 2013. A variety of experiments were conducted on the TRACT 1 test to evaluate Anthropomorphic Test Device (ATD) responses, seat and restraint performance, cargo restraint effectiveness, patient litter behavior, and photogrammetric techniques. Combinations of Hybrid II, Hybrid III, and ES-2 ATDs were placed in forward and side facing seats. In addition, two standing ATDs were used to evaluate the benefit of Mobile Aircrew Restraint Systems (MARS) versus a standard gunner’s belt. Photos of the cabin ATDs used in TRACT 1 are shown in Figure 3. The pilot and co-pilot ATDs are shown in Figure 4. Of the 15 ATDs in TRACT 1, 13 were instrumented to record occupant forces, accelerations, and restraint forces. Occupant results were compared against injury criteria.

The cabin subfloor contains aluminum shear web panels that could be readily swapped for other composite concepts. These composite concepts may provide equal or better energy absorptivity compared to the aluminum shear webs at lower weight. TRACT 1 was used to establish baseline cabin floor loads.

The TRACT 1 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 (Ref. 2), 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 (Ref. 3) 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.

In addition to occupant loading, the structural response of the airframe was assessed from accelerometers located throughout the airframe and three-dimensional photogrammetric techniques. Photographs of the impact sequence for TRACT 1 with full-field photogrammetry of the lateral deformation are shown in Figure 5. The lateral deformations are clearly visible just at window height, indicating dilation of the airframe as the understructure impacts.

An overview of results of all the experiments on TRACT 1 is discussed in Ref. 4. Detailed discussions for a cockpit active restraint experiment and the MARS experiment are provided in Ref. 5 and Ref. 6, respectively. TRACT 1 was considered a highly successful collaboration among crashworthiness and injury biomechanics organizations. TRACT 1 demonstrated, from both a technological and economic perspective, the benefit in conducting full-scale crash testing to evaluate safety systems and airframe crashworthiness.



Figure 3. TRACT 1 Cabin ATDs



Figure 4. TRACT 1 Pilot and Co-pilot ATDs

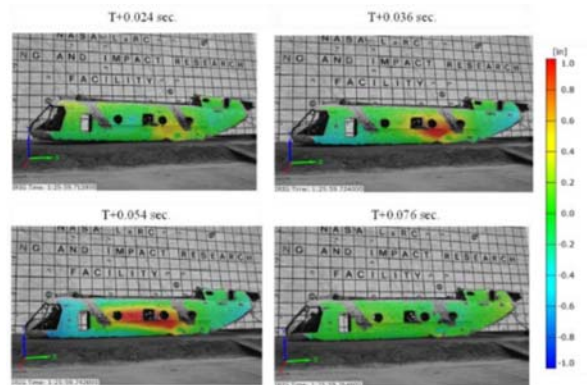


Figure 5. TRACT 1 Impact Sequence and Lateral Displacement from Photogrammetry

TRACT 2 TEST ARTICLE DEVELOPMENT

Upon completion of TRACT 1, preparations for the crash test of the second CH-46E airframe began. Agreements with the following TRACT 1 collaborators were extended for participation in TRACT 2:

- The Naval Air Systems Command (NAVAIR), Human Systems Department, Crashworthy Systems Branch, 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, 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, investigates air and ground warfighter response to dynamic loading, including blast, ballistics, and impact.

- Cobham Mission Systems develops restraint systems for fixed and rotary wing and ground vehicles.

Additional agreements were developed and instituted with two organizations:

- The Australian Cooperative Research Centre for Advanced Composite Structures (ACS) and 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.

The primary focus for NASA and the RW project was development of retrofit composite airframe concepts. One advantage of the CH-46E cabin was the fact that its frame sections were 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, containing 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 section is discussed in Ref. 7. Results from the development of the sinusoid section is described in Ref. 8

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 subfloor the TRACT 2 test article in Figure 6. 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 7.



(a) ACS-DLR Composite Subfloor



(b) NASA Composite Subfloors

Figure 6. Composite Subfloor Retrofit for TRACT 2

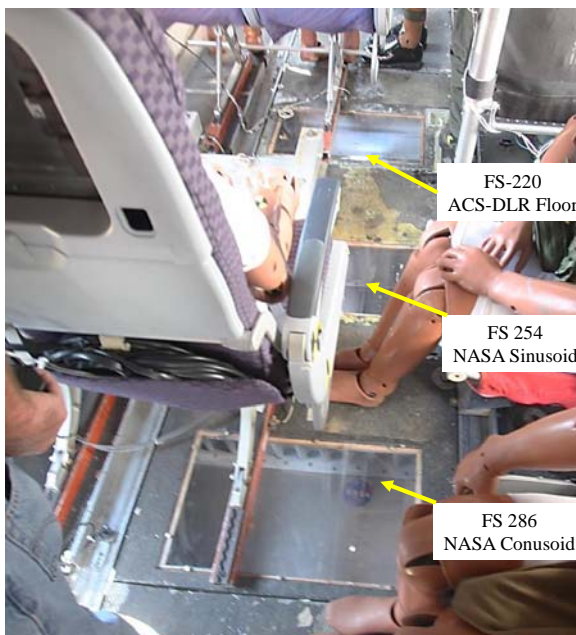


Figure 7. Cabin Installation over Subfloors

There were several key modifications to the airframe prior to conducting the test. Fiberglass panels, fabricated for TRACT 1, were attached to the underside of the cockpit enclosure to reduce plowing of the exposed cockpit. Two angle channel beams used for TRACT 1 were bolted along the outer sidewalls three inches above the waterline (WL) to

provide hard points for the swing and pullback cables. The location of the swing 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 random pattern of over 8,000 one-inch diameter dots were applied to the airframe skin on the left side. The motion of the dots could be tracked, and the airframe full-field deformation and kinematics could be computed. These modifications are shown in Figure 8.

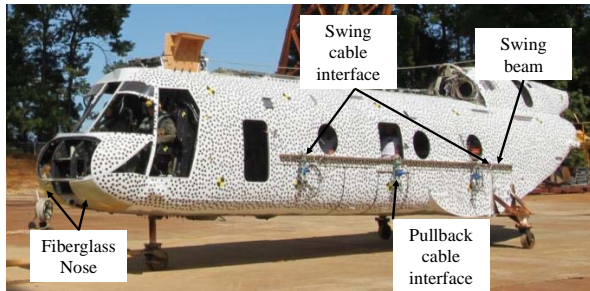


Figure 8. TRACT 2-Swing Beams and Photogrammetric Dot Pattern

Eighteen unique experiments were defined for TRACT 2. The airframe FS and locations of each experiment are illustrated in Figure 9. The experiments are listed in Table 1, and photos of their locations are shown in Figure 10-Figure 12. Summaries of select experiments are described herein.

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 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 crew seat configuration was used for comparison in Experiment 2. Two NAVAIR supplied, fully outfitted 50th-percentile aerospace ATDs were seated in the CH-46E crew seats.

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

The Mobile Aircrew Restraint System (MARS) system was developed by Cobham Mission Systems as a variation on the MA-16 inertia reel. 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. Experiments 4 and 5

contained NAVAIR 5th percentile pedestrian male ATDs in rear and side facing positions (Ref. 9).

The occupant responses in floor mounted seats above the composite subfloors were tracked with four different ATDs. Two pairs of donated double seats that have been certified to Part 25 requirements (Ref. 10) were used. A 50th percentile Hybrid II (Experiment 7) and 50th percentile FAA Hybrid III (Experiment 8) were seated in the first pair above 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 above the NASA conusoid floor (Experiment 12). A ballast mass of 600-lb was attached over the sinusoid floor (Experiment 10) to represent comparable mass loading.

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.

An energy absorbing troop seat was developed by Safe, Inc. and evaluated by NAVAIR. The seat is attached to two telescoping vertical tubes using selectable profile energy absorbers (Ref. 11). 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 excessively deforming. 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). CARGO PMO supplied a standard 1-man 8-G troop bench seat (Experiment 15) and the CRTS (Experiment 16). NASA provide two 50th-percentile Hybrid II ATDs.

A load-limiting cargo restraint was developed by NAVAIR and Penn State University that uses a stitch ripping device (SRD). Energy is absorbed by webbing extension, thread rupture and stitch slippage (Ref. 12). One 500-lb sliding mass was connected to an SRD and another 500-lb mass connected to a standard webbing restraint with forces measure by end line load cells (Experiment 17).

USAARL is investigating performance issues related to litters and litter patients in the cabin of a rotary wing airframe during a crash event. 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 one non-instrumented ATD (Experiment 18).

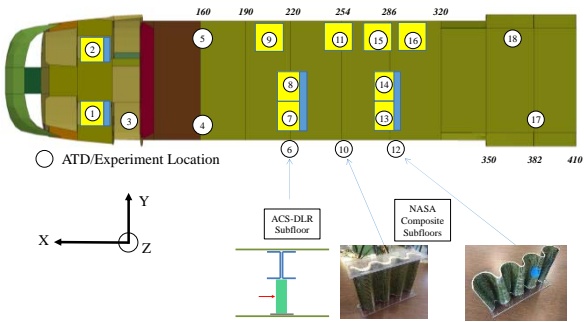


Figure 9. Experiment and ATD Locations- Top View

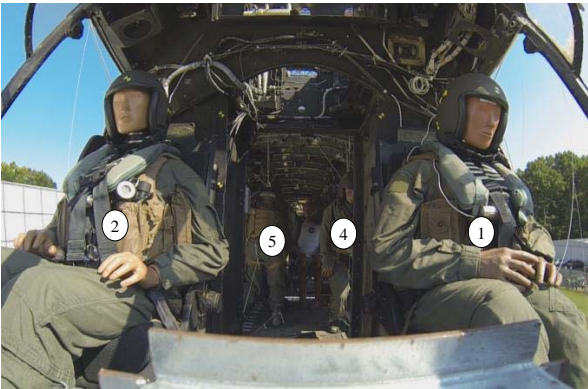


Figure 10. TRACT 2 Experiments- Cockpit and Front Cabin

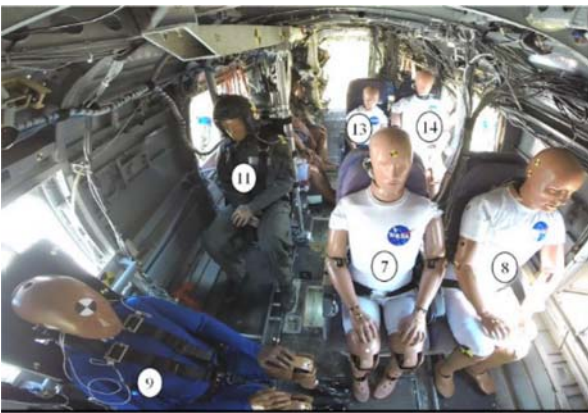


Figure 11. TRACT 2 Experiments- Mid Cabin



Figure 12. TRACT 2 Experiments- Aft Cabin

Table 1. TRACT 2 Experiments

Experiment/ ATD	Description	Provided by
1	50 th Aerospace ATD w/ PARS	NAVAIR/ Cobham
2	50 th Aerospace ATD w/o PARS	NAVAIR
3	ELT	NASA
4	5 th pedestrian standing sideways ATD w/ MARS	NAVAIR
5	5 th pedestrian standing rearward ATD w/ MARS	NAVAIR
6	Corrugated composite subfloor	ACS-DLR
7	50 th Hybrid II ATD	NASA
8	50 th FAA Hybrid III ATD	NASA
9	ES-2/Hybrid III 50 th ATD, side- facing in CACS seat	NAVAIR (seat), CAMI (ATD)
10	Sinusoid Sandwich subfloor	NASA

Experiment/ ATD	Description	Provided by
11	50 th Aerospace ATD in ceiling-mounted troop seat	NAVAIR
12	Conusoid subfloor	NASA
13	95 th Hybrid III ATD	NASA
14	5 th Hybrid III ATD	NASA
15	50 th Hybrid II ATD in one-man troop seat	NASA (ATD), CARGO PMO (seat)
16	50 th Hybrid II ATD in CRTS	NASA (ATD), CARGO PMO (seat)
17	Cargo restraint	NAVAIR
18	Patient Litter	USAARL/ NAVAIR (ATD)

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.

Over 40 high speed and high definition cameras were mounted onboard and on the perimeter of the test impact location to conduct 2-D and 3-D photogrammetry of the vehicle. All external high speed cameras all 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 were positioned to track ATD motion and the response of the composite subfloor.

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 MARS standing dummy.

A weight and balance was conducted on the TRACT 2 test article. The test article was suspended by three cables over the west side of LandIR. Load cells on all three cables measured the loads at zero pitch and 20 degree pitch. Figure 13 shows the weight and balance test. The weight of the test article (minus the nose and main wheel assemblies) was 10,534-lb. The longitudinal CG was at FS 262.8. The lateral CG was less than ½-inch off the centerline, and the vertical CG was 10 inches below the WL. The weight and CG location were similar to TRACT 1, and confirmed that the placement of swing and pullback cable interfaces on the test article was acceptable.



Figure 13. TRACT 2 Weight and Balance Test

One week prior to the test, a dry run was conducted. The fully instrumented test article was moved to the impact area underneath the gantry. All checklist procedures to align swing cables, switch from external to onboard power, hoist the test article to drop height, and trigger and download data and video were performed. The dry run was conducted without any complications in execution and performance verification. The dry run is shown in Figure 14.



Figure 14. TRACT 2 Dry Run

TRACT 2 RESULTS

The TRACT 2 test was conducted on 1 October 2014. Less than 5% of the 360+ instrumentation channels showed signal drop out from cable detachment or sensor damage. One onboard high speed camera (out of 12) and two high definition cameras (out of 11) did not record.

Instrumentation and video data were provided to all primary collaborators. The experiments relating to airframe performance and NASA ATD response are presented. Public dissemination of other collaborator results will be based on the collaborators' discretion.

Figure 15 shows the TRACT 2 orientation just prior to impact. The nominal and actual impact conditions are listed in Table 2. 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 photo time lapse from an external high-speed camera is shown in Figure 16. The region forward of the stub wing box begins to crush 0.016-sec after impact. Cockpit touchdown occurs at 0.045-seconds. At 0.055-sec, the subfloor skin between FS 190 and FS 220 begins to dimple inwards. The aft cabin and tail rebounded starting at 0.090--sec, 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.

Table 2. TRACT 2 Impact Conditions

	Nominal	Actual
Vertical velocity	26 ft./sec	25.4-ft/sec
Horizontal velocity	35 ft./sec	33.7-ft/sec
Pitch	2° nose up	2.6° nose up
Roll	0°	3.6°

	Nominal	Actual
Yaw	0°	2.5°



Figure 15. TRACT 2, Front View, Prior to Impact

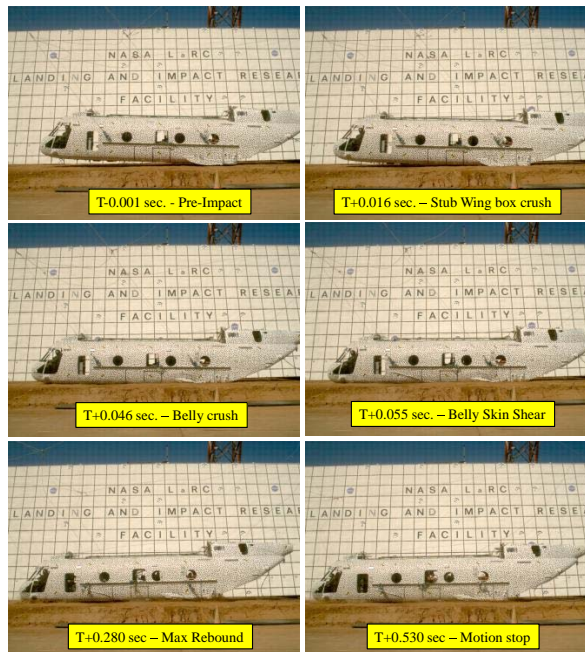


Figure 16. Impact sequence of TRACT 2 test

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 17. The layered soil with a softer base yielded a large crater depth, as deep as 9-inches.

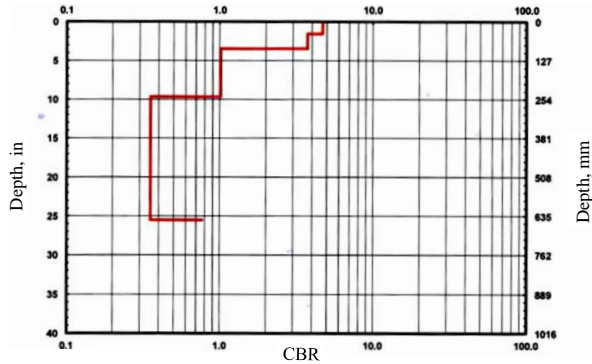


Figure 17. TRACT 2 Soil Strength

Figure 18 shows a plot of the horizontal velocities for the airframe at the longitudinal 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 18. 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).

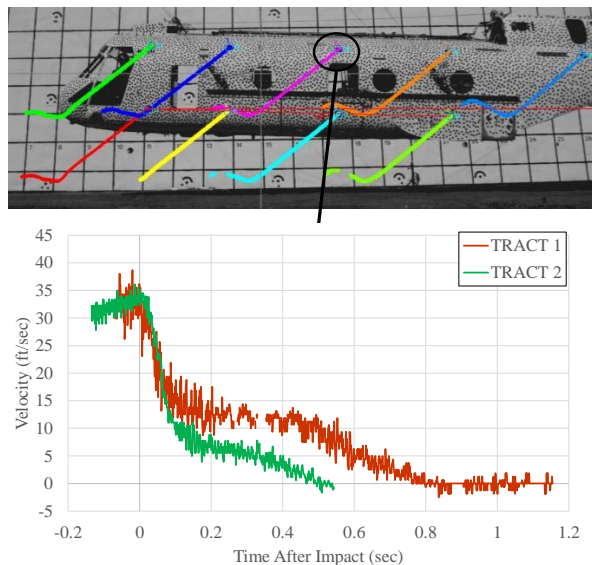


Figure 18. Comparison of TRACT 1 and TRACT 2

Horizontal Velocities

Full-field lateral displacements of the outer surface of the sidewall skin are fringe plotted in Figure 19. 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.

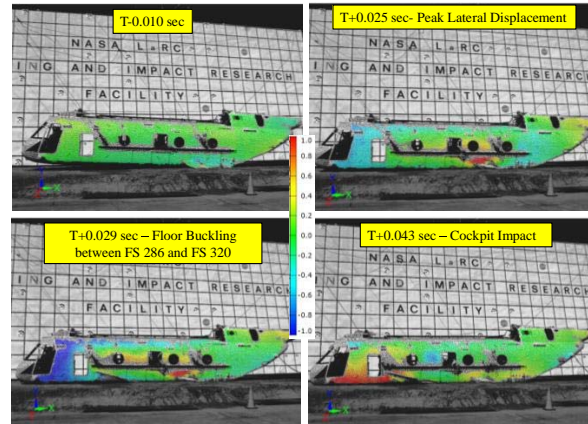


Figure 19. TRACT 2 Lateral Displacement from Photogrammetry

Cabin Results

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 20 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.

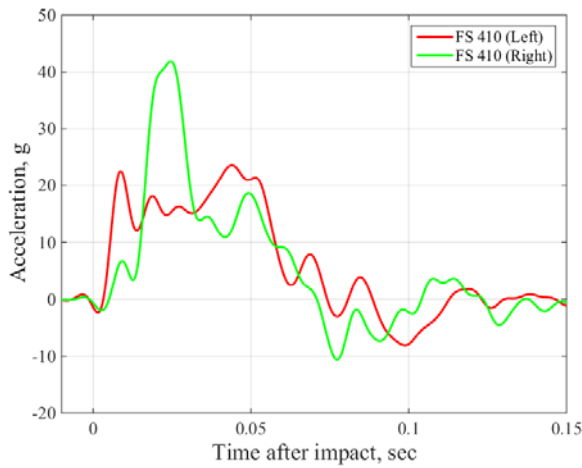


Figure 20. TRACT 2 Aft Cabin Frame Vertical Accelerations- Adjacent to Floor

A photo of the understructure after impact is shown in Figure 21. 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 22. 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 longitudinal 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 longitudinal shearing was evident in the cabin subfloors.

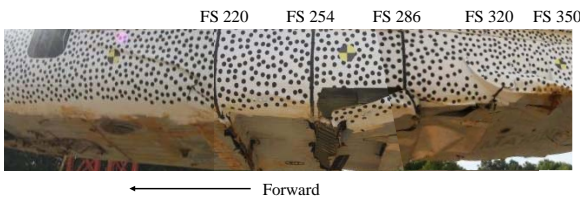


Figure 21. TRACT 2, Post-test Photo, Airframe Deformation

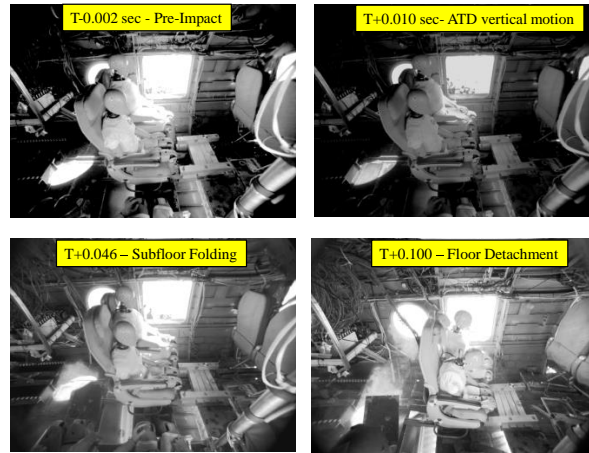


Figure 22. TRACT 2 Cabin, Impact Sequence

All accelerations are low-pass filtered to the SAE J211 standard, using a Channel Frequency Class (CFC) 60 (Ref. 13) for vehicle accelerations. Vertical acceleration plots near the cabin floor centerline reveal the lack of subfloor energy absorption and load path distribution seen in TRACT 1. Figure 23 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.

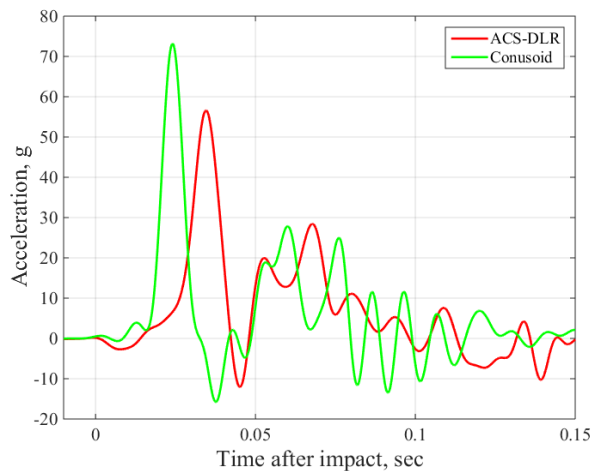


Figure 23. TRACT 2 Mid-Cabin Floor Vertical Accelerations

The vertical responses from accelerometers mounted on cabin frames are plotted in Figure 24 and 25. Figure 24 shows the vertical accelerations on the frames at floor-height. Figure 25 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 increases going forward in the cabin. This negative component is evident in

the acceleration response of FS 160 at plot around 0.020-seconds, as shown in Figure 24.

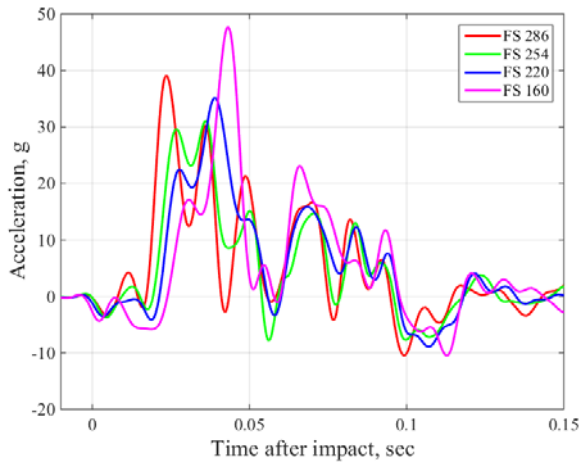


Figure 24. TRACT 2 Mid Cabin Frame Vertical Accelerations- Adjacent to Floor

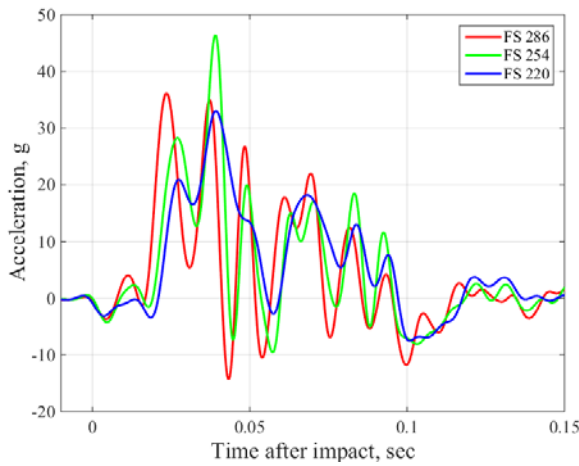


Figure 25. TRACT 2 Vertical Accelerations- Sidewall

The longitudinal accelerations as recorded by accelerometers mounted on cabin frames are plotted in Figure 26. 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.

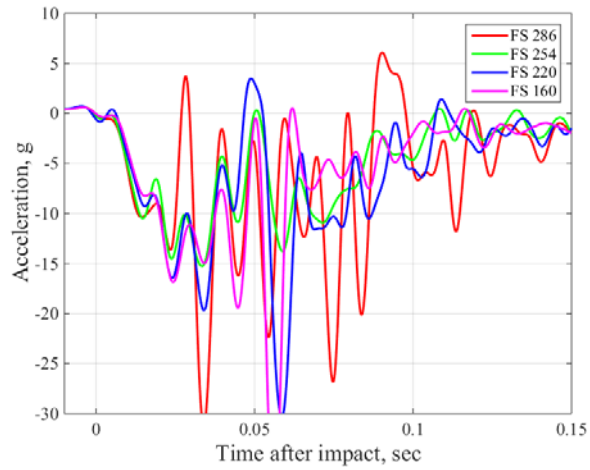


Figure 26. TRACT 2 Cabin Frame Longitudinal Accelerations- Adjacent to Floor

The resulting occupant responses are best explained with a plot of lumbar load versus time. Figure 27 shows lumbar load which has been low-pass filtered using CFC 1000. A compression force is defined to be positive. The NASA ATDs are on lap-belted passenger seats. The CAMI and NAVAIR/Safe ATDs are on energy absorbing troop seats with five-point harnesses. The lumbar loads for the two NASA 50th ATDs exceed 2,300-lb, well above the 1,500-lb lumbar load limit for seat certification. The lumbar loads for the 5th female and 95th male are 936-lb, and 1,544-lb, respectively. There is not a specific FAA lumbar load requirement defined for 5th and 95th ATDs. However, the DOD has recommended injury limits of 1,281 lb. for the 5th female and 2,534 lb. for the 95th male (ref. 14). The DOD recommendations for the 50th ATD are scaled up relative to the FAA requirement. Therefore, equivalent civilian requirements for the 5th and 95th would likely be lower. It is apparent that lumbar loads for the 5th female and 95th male are near or below injury tolerance levels. Of note, the 5th and 95th ATD lumbar loads transition from compression to tension because of the forward torso flail. The lumbar loads for the CAMI and NAVAIR/Safe ATDs are 1,581-lb and 509-lb, respectively. The CAMI ATD is at the tolerance level, while the NAVAIR/Safe ATD is well below.

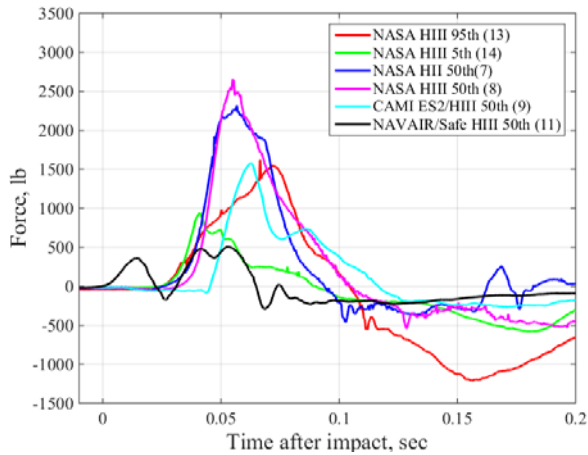


Figure 27. TRACT 2 Cabin ATDs, Lumbar Load

Cockpit Results

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 28. 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.

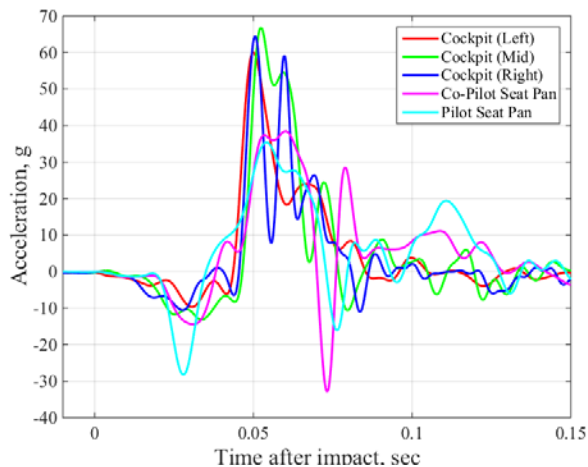


Figure 28. TRACT 2 Vertical Accelerations- Cockpit

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

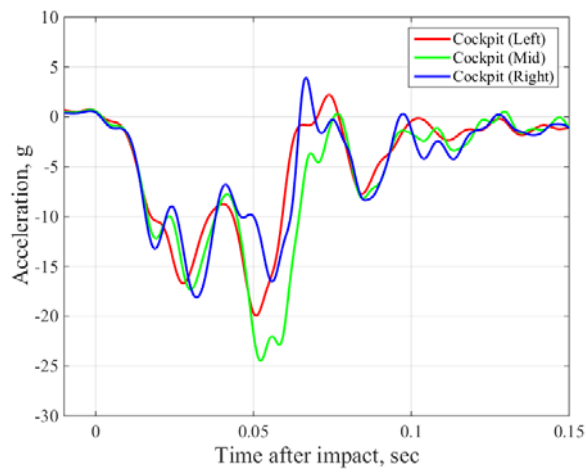


Figure 29. TRACT 2 Longitudinal Accelerations- Cockpit

The response of the pilot and co-pilot ATDs is shown with time lapse photos in Figure 30. Just after tail impact, the ATDs elevate out of their seat due to the negative acceleration, then re-contact the seat at 0.050-seconds. The torsos begin to pitch forward at 0.090-seconds. Maximum flail occurs at 0.140-seconds.

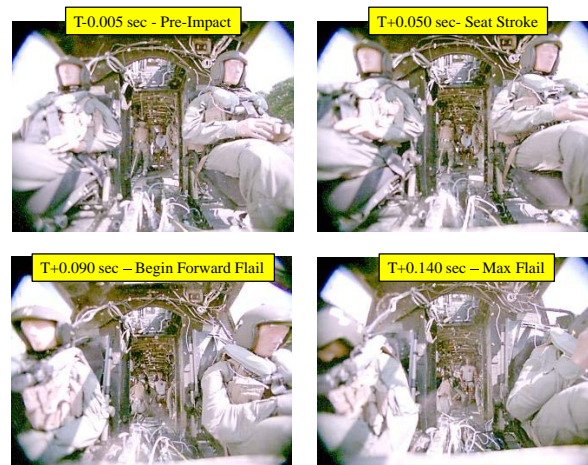


Figure 30. TRACT 2 Cockpit- Impact Sequence

The lumbar loads for the pilot and co-pilot are filtered to CFC 1000 and plotted in Figure 31. Both lumbar loads are within the DOD limit of 2,096-lb, indicating good performance by the crew seat energy absorbers. The peak co-pilot load was 900-lb, and the peak pilot load was 1,450-lb. The lumbar loads are lower than those seen by the co-pilot and pilot in TRACT 1, where lumbar loads were 2,200-lb and 1,500-lb, respectively. In both TRACT 1 and TRACT 2, there were significant differences between the pilot and co-pilot lumbar loads. This may be attributed to the changing positions of the ATDs as the seat strokes, and also the distribution of loads

between their pelvis and feet. The lumbar loads are in tension as the ATDs flail forward.

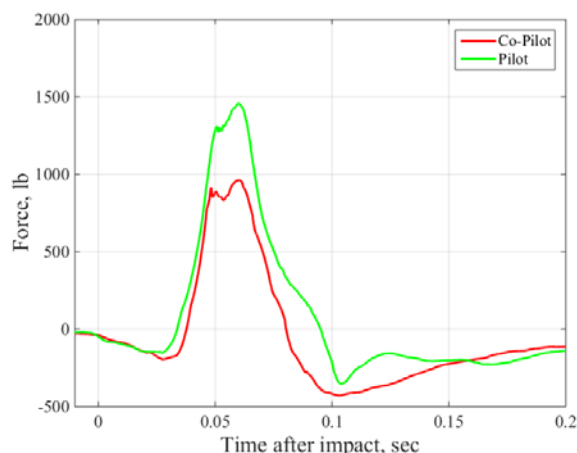


Figure 31. TRACT 2 Co-Pilot and Pilot Lumbar Loads

CONCLUSION

The TRACT 2 full-scale crash test of a CH-46E helicopter airframe was conducted in October 2014 at the LandIR facility. The impact test conditions (33-ft/s forward and 25-ft/s vertical velocity with a 2.5-degree nose-up pitch onto soft soil) were considered lower than typical DOD qualification levels, but severe enough to approach civilian survivability envelopes. Impact conditions were similar to the TRACT 1 test, with some additional roll and yaw. The primary difference in the 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 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. 18 unique 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 Aircrew Endurance Vest and MARS
- Full-field three-dimensional photogrammetry data collection
- A Hybrid III ATD with ES-2re head and neck, on a sidewall-mounted CACS troop

- Comparison of the CRTS sidewall mounted troop seat 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 longitudinal accelerations were consistent throughout the aircraft at approximately 15-g with a duration of 0.1-seconds. The vehicle slide out distance was nearly half that of TRACT 1. These accelerations were higher than TRACT 1, due to a combination of factors. One factor was higher soil moisture, causing a reduction in stiffness and increased soil cratering. Along with that, 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 longitudinally before they could undergo stable crushing. More longitudinal 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.

ATDs were oriented in forward facing, side facing, and standing positions. The lumbar loads were within acceptable injury limits for the ATDs located in the pilot and co-pilot seats, the CACS seat, and the Safe, Inc. seat. Lumbar loads exceeded injury limits for the two 50th-percentile ATDs, and near or below injury limits for the 5th- and 95th-percentile ATDs.

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 longitudinal 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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