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LWH & ACH Helmet Hardware Study

Ronald L. Holtz
Peter Matic

Multifunctional Materials Branch
Materials Science and Technology Division

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NRL conducted a series of basic tests to characterize the properties of helmet screws and nuts used with the Light Weight Helmet (LWH) and Advanced Combat Helmet (ACH). The testing included basic dimensional measurements, Rockwell hardness and Vicker's microhardness measurements, metallographic examination of the grain microstructure, basic chemical composition, tensile strength, screw/nut thread pull strength, and a drop-weight impact test. Information was obtained for sets of screws and nuts taken from LWH and ACH helmets that have previously passed acceptance tests. This information is used as reference values for a series of recommended tests that can be applied to new batches of helmets or replacement screws, to detect any significant changes in the helmet hardware characteristics that could indicate a change of the ballistic performance.

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Helmet hardware	Tensile strength	Impact test
Hardness	Grain structure	

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EXECUTIVE SUMMARY

The Naval Research Laboratory conducted a series of laboratory tests to characterize the properties of helmet screws and nuts used with the Light Weight Helmet (LWH) and Advanced Combat Helmet (ACH). The testing included dimensional measurements, Rockwell hardness and Vicker's microhardness measurements, metallographic examination of the grain microstructure, chemical composition, tensile strength, screw/nut thread pull strength, and a drop-weight impact test.

Information was obtained for sets of screws and nuts taken from LWH and ACH helmets that had previously passed acceptance tests. This information was used as reference values for a series of recommended tests that can be applied to new batches of helmets or replacement screws, to detect any significant changes in the helmet hardware characteristics that could indicate a change of the ballistic performance.

For the helmet screws, recommended initial screening consists of visual examination and dimensional measurements; intermediate property screening tests are surface hardness, grain microstructure examination, cross-sectional hardness, thread and slot examination, and chemical analysis; and more advanced testing includes thread strength, screw tensile strength, and drop-weight impact testing.

For the helmet nuts, NRL recommends visual and dimensional screening, followed by a thread pull strength test. Several optional tests are suggested for diagnostic purposes if the pull strength test fails.

LWH & ACH HELMET HARDWARE STUDY

1. BACKGROUND & SCOPE

Steel screws and nuts used in the Lightweight Helmet (LWH) and Advanced Combat Helmet (ACH) to secure the helmet chinstrap retention system are required to resist fracture upon direct impact by 9 mm full metal jacket bullets to reduce risks of warfighter head injuries from hardware fragments as well as bullets or bullet fragments. Currently, this hardware is subjected to a ballistic impact test along with the helmet shell, and there is a static pull test for the chinstrap system; otherwise, there are *no specific materials property requirements for the hardware alone*. It is desired to better define the fastener hardware characteristics without resorting to ballistics testing, in order to reduce the need for ballistic testing of the helmets to qualify the fasteners. The significance to DoD will be reducing the cost and time associated with lot ballistic tests of helmets, and better understanding of the variables that affect the reliability of the fasteners. The objective of this study therefore was to define a set of non-ballistic, laboratory tests for helmet fastener hardware properties that can provide an indication of expected ballistic performance. It is not clear at present how acceptable behavior in the ballistic test, i.e. no hardware fragments entering the clay head form backing, corresponds to underlying materials properties of the hardware. The challenge is to establish a valid empirical correlation between the ballistic behavior demonstrated to resist fragmentation and prospective non-ballistic laboratory test methods.

Figure 1. Helmet hardware tested by NRL in this study. Both ACH and LWH use the same nuts.

Impact properties generally do not depend directly upon simple measures such as hardness, tensile strength, composition, or grain structure. However, there tends to be enough of a *correlation* that if two materials have similar hardness, tensile strength, composition and grain structure, then they are likely to have similar impact properties. Thus the approach of this study was to document the basic characteristics of samples of helmet hardware taken from batches of helmets that had previously passed ballistic testing, and adopt those as reference material properties. The rationale is that other batches of hardware with similar characteristics should have similar ballistic properties.

In addition to easily obtained, basic metallurgical characteristics including hardness and grain structure, NRL devised a proof test for testing the strength of the screw-nut threaded connections, a tensile test for estimating tensile strength of screws, and a low energy impact test for the screw heads. These latter three tests require more specialized equipment than the basic metallurgical tests, so in our recommendations we suggest doing a series of simpler tests on the screws first to determine if the basic characteristics such as hardness and grain structure are different enough from the reference hardware to warrant conducting the additional testing. The nuts are not directly subject to bullet or fragment impact, so impact testing is not necessary for the nuts. The main concern with the nuts is that the threaded connection with the screw is

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sufficiently strong. That can be measured directly with the screw-nut thread proof test; nothing has to be inferred, as is necessary for ballistic resistance of the screw heads. Further, provided the nut threads are sufficiently strong, the details of the grain structure, composition, etc., are not particularly important. Thus metallurgical testing of the nuts is deemed to be optional, provided that the thread proof test is available.

It should be noted that it is not the intent of this study to create specifications for procurement contracting purposes, but only to provide basic information on the properties of helmet hardware already in use, against which new hardware can be compared. Again, as mentioned above, the presumption is that hardware of similar configuration, dimensions, and similar materials properties is expected to have similar ballistic performance in the helmet. On the other hand, significant *deviations* from the configuration, dimensions or materials properties of current hardware potentially could indicate potential differences in ballistic performance in the helmet application, and thus independent ballistic verification would be prudent in those cases. Further, the scope of this report does not include identifying potential deficiencies with existing hardware alloys, or identifying potentially better alloys for helmet hardware.

2. SUMMARY OF TESTS DONE

Marine Corps Systems Command arranged for NRL to receive three each of LWH and ACH helmets from lots that had previously passed required acceptance tests. Screws and nuts were removed from these helmets to be used as reference specimens. Additionally, a quantity of replacement hardware of current manufacture was procured from Gentex, Inc., the vendor of the helmets, for comparison. A summary of the specimen information is in Table I.

TABLE I – SUMMARY OF HARDWARE SPECIMENS

Helmet Type	*Item*	*Description*	*Source*	*Date*
LWH	Screw	Reference LWH Screw	Gentex LWH Helmet Contract # DAAD16-99-D-1015	04/09
LWH	Nut	Reference LWH Nut	Gentex LWH Helmet Contract # DAAD16-99-D-1015	04/09
ACH	Screw	Reference ACH Screw	Gentex ACH Helmet Contract # W911QY-05-D-0003	11/06
ACH	Nut	Reference ACH Nut	Gentex ACH Helmet Contract # W911QY-05-D-0003	11/06
LWH	Screw	Replacement LWH Screw	Gentex Replacement Part Part # B11816-2	01/11
ACH	Screw	Replacement ACH Screw	Gentex Replacement Part Part # B12190-1	01/11
ACH & LWH	Nut	Replacement Nut	Gentex Replacement Part Part # B11815-1	01/11

2.1 External Characteristics – Dimensions, Vicker’s Hardness

After visual examination to ensure that none of the hardware pieces were anomalous, we measured all of the key dimensions of the reference screws and a number of the replacement screws. These dimensions are defined in Figure 2 and are tabulated in Table IIA. A stainless steel caliper was used with a precision of ±0.001 inch. Measurement uncertainties generally are ±0.001 inch on most dimensions, with the following exceptions: slot widths and depths ±0.002, head heights ±0.003, shoulder lengths ±0.005 and overall lengths ±0.010. The maximum and minimum of key dimensions for purposes of comparing to the reference screws were adopted as the three standard-deviation range of the measured reference screws. Table IIB lists the dimensions of the replacement screws. We note that the dimensions of the replacements screws appear to have tighter tolerances than the reference screws.

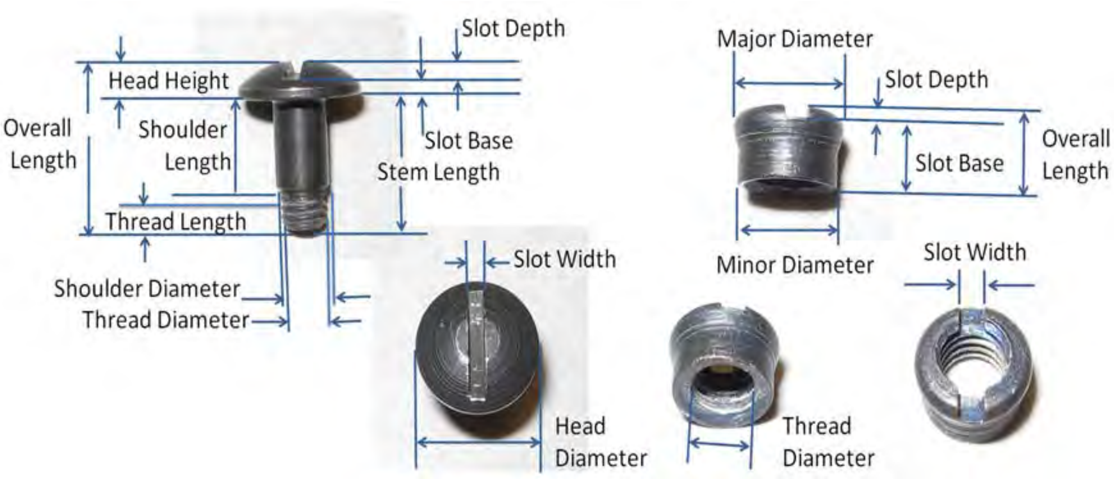

Figure 2. Definitions of screw and nut dimensions listed in Table II.

Vicker's microhardness measurements (*ASTM E384 Standard Test Method for Microindentation Hardness of Materials*) were made on the exterior surfaces of screws and nuts as a preliminary assessment and the averages and ranges of HV values listed in Table III. We found the range of surface hardness values to be quite broad with large variations, and therefore of limited use as a hardware definition, but of some value for rough screening purposes since this measurement is simple and quick. Since the Vicker's microhardness indentations are comparable to the grain size of the materials, variations of the values are associated with microscopic variations of the materials properties and not necessarily due to variations in manufacturing. For the recommended lot testing of screws described below in Section 3.1, we adopted both the average and the overall range of values measured on the reference hardware as reference values. However, we do not recommend use of surface Vicker's microhardness testing for characterizing the nuts, because, as indicated in Table III, there was a 350% difference between the LWH nuts and ACH nuts.

2.2 Metallographic Examination

Some of the screws and nuts were cut in half lengthwise, mounted in epoxy, and polished, as shown in Figure 3, then the grain microstructure examined via optical metallography using conventional techniques (*e.g. ASTM E3 Preparation of Metallographic Specimens*). The hardware pieces were cross-sectioned using a low-speed diamond saw, and mounted in epoxy and cured at room temperature. Initial manual sanding of the cut surfaces was no coarser than 600 grit silicon-carbide paper. Final polishing was done with one micron or finer diamond polishing compound, which is

Figure 3. Example of cross-sectioned screw (ACH in this example) and nut mounted in plastic and polished. The marks on the surface of the screw are Rockwell hardness indentations.

TABLE IIA –REFERENCE HARDWARE DIMENSIONS

Hardware Item	*Dimension*	*Average [inch]*	*± St.Dev. [inch]*	*Minimum* [inch]*	*Maximum* [inch]*
Reference LWH Screws	Head diameter	0.492	0.002		
“	Head height	0.131	0.001	0.129	
“	Slot depth	0.050	0.004		0.062
“	Slot width	0.064	0.002		0.070
“	Slot base	0.075	0.004	0.063	
“	Shoulder diameter	0.216	0.001	0.213	
“	Shoulder length	0.323	0.006		
“	Stem length	0.479	0.006		
“	Overall length	0.608	0.002		
“	Thread outside diameter	0.186	0.001	0.181	0.189
“	# of fully-formed threads	> 3		3	
Reference ACH Screws	Head diameter	0.563	0.001		
“	Head height	0.139	0.004	0.127	
“	Slot depth	0.058	0.004		0.070
“	Slot width	0.063	0.001		0.066
“	Slot base	0.076	0.002	0.070	
“	Shoulder diameter	0.245	0.001	0.242	
“	Shoulder length	0.323	0.007		
“	Stem length	0.482	0.003		
“	Overall length	0.618	0.003		
“	Thread outside diameter	0.184	0.001	0.181	0.189
“	# of fully-formed threads	> 3		3	
Reference LWH Nuts	Major diameter	0.283	0.001		
“	Minor diameter	0.250	0.001		
“	Overall length	0.168	0.001		
“	Thread inside diameter	0.158	0.002	0.152	0.164
“	Slot depth	0.035	0.005		0.050
“	Slot width	0.065	0.001		0.068
“	Slot base	0.128	0.002	0.122	
Reference ACH Nuts	Major diameter	0.283	0.002		
“	Minor diameter	0.252	0.001		
“	Overall length	0.170	0.003		
“	Thread inside diameter	0.158	0.002	0.152	0.164
“	Slot depth	0.037	0.003		0.046
“	Slot width	0.061	0.002		0.067
“	Slot base	0.129	0.003	0.120	

** Estimated minimum and maximum values = average +/- 3 standard deviations.*

TABLE IIB –REPLACEMENT HARDWARE DIMENSIONS

Hardware Item	*Dimension*	*Average [inch]*	*± St.Dev. [inch]*
Replacement LWH Screws	Head diameter	0.493	0.001
“	Head height	0.132	0.002
“	Slot depth	0.049	0.003
“	Slot width	0.057	0.001
“	Slot base	0.081	0.002
“	Shoulder diameter	0.212	0.001
“	Shoulder length	0.327	0.002
“	Stem length	0.484	0.001
“	Overall length	0.613	0.001
“	Thread outside diameter	0.186	0.001
“	# of fully-formed threads	> 3	
Replacement ACH Screws	Head diameter	0.562	0.001
“	Head height	0.139	0.001
“	Slot depth	0.046	0.001
“	Slot width	0.060	0.001
“	Slot base	0.092	0.001
“	Shoulder diameter	0.243	0.001
“	Shoulder length	0.329	0.002
“	Stem length	0.481	0.002
“	Overall length	0.622	0.003
“	Thread outside diameter	0.185	0.001
“	# of fully-formed threads	> 3	
Replacement Nuts	Major diameter	0.282	0.001
“	Minor diameter	0.252	0.001
“	Overall length	0.168	0.001
“	Thread inside diameter	0.163	0.002
“	Slot depth	0.042	0.003
“	Slot width	0.059	0.002
“	Slot base	0.127	0.004

TABLE III – EXTERIOR VICKER’S MICROHARDNESS

Hardware Item	*Locations*	*Average**	*Minimum*	*Maximum*	*±St. Dev.*
Reference LWH Screws	Flat part of head	135	122	147	11
Reference LWH Screws	Shoulder	146	124	167	12
Reference ACH Screws	Shoulder	89	80	103	9
Reference LWH Nuts	Side of nut	147	134	167	9
Reference ACH Nuts	Side of nut	41	31	62	10

**Two screws and two nuts of each type, five measurements each.*

sufficient to reveal the grain structures, although final polishing with colloidal silica and/or colloidal alumina polish to 0.05 or 0.03 micron is recommended. Assuming that the screw and nut materials to be examined are similar to those examined by NRL, immediately prior to metallographic examination the polished surfaces of the screw material are etched at room temperature with 2% Nital (2% nitric acid in ethanol) for 45 seconds. The nuts were etched for only 15 seconds. Optical magnifications of 200X to 500X are needed to see the important details of the grain structures.

Figure 4 shows the grain structures of the reference LWH and ACH screws removed from helmets (manufactured in April 2009 and November 2006, respectively) compared to the replacement screws obtained from Gentex in January 2011. The grain structures are all similar, although there are some differences between the grain structures of the replacement LWH and ACH, and the reference screws removed from helmets in several respects. The pearlite banding is a little less coarse in the replacement screws. The inclusions in the replacement screws are longer, thinner, there are more of them, but fewer of them are cracked than in the screws removed from helmets. These differences are probably within the variations allowed in the alloy definitions; i.e. variations between different stocks of the same alloy.

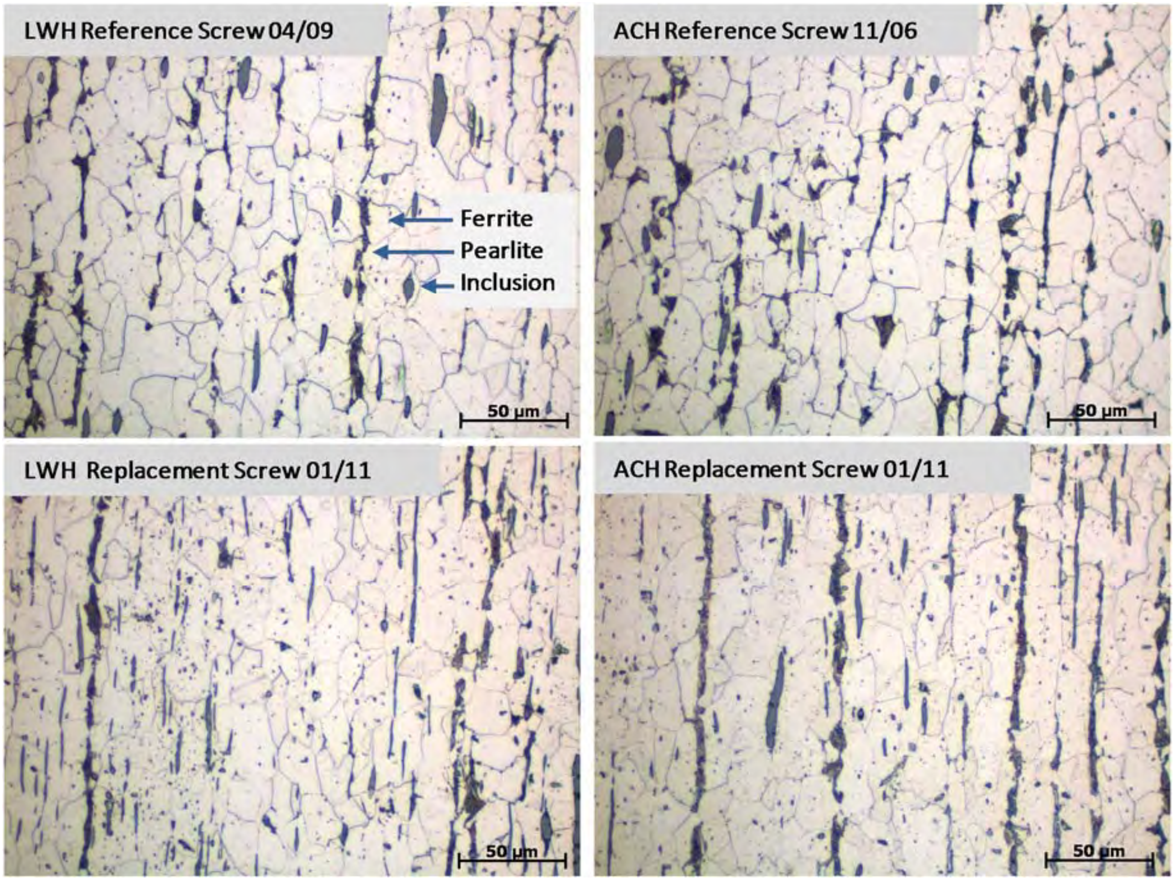

Figure 4. Grain microstructures of screw cross-sections after polishing and nital etching as described in the text. The longitudinal direction of the screw is vertical in the image. The lightest polyhedra are the ferrite grains. The linearly aligned dark features are pearlite banding. The smaller isolated, elongated, lighter grey objects, many of which are cracked, are manganese sulfide inclusions, often referred to as stringers.

The ASTM grain size numbers, G, of the ferrite grains as determined by a linear intercept method per *ASTM E112 Standard Test Methods for Determining Average Grain Size*, are between 9.3 and 10.1 for all screws, both reference and replacement lots. The corresponding *average* ferrite grain diameters are all within the range of 10 to 15 μm.

Figure 5 shows the grain structures of several nuts examined by NRL. There are more significant differences between the various nuts. The LWH nut (From helmet dated 04/09) and ACH nut (from helmet dated 11/06) both are primarily fine pearlite, but the ACH nut has some bands of ferrite. These two materials are similar enough that they are probably variations between different stocks of raw material. The replacement nut (obtained from Gentex 01/11) on the right has a very different microstructure than the other two. It appears to either have undergone an additional grain-refining heat treatment, or could be a different alloy altogether.

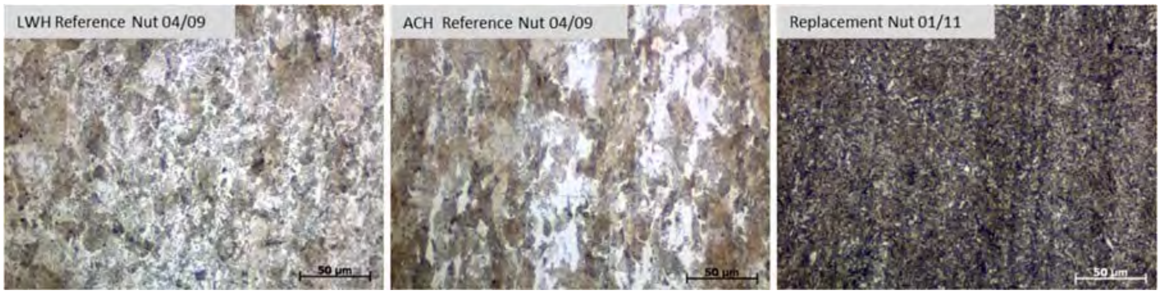

Figure 5. Grain microstructures of nut cross-sections after polishing and nital etching as described in the text. The longitudinal axis of the nut is vertical in the image

Principal chemical composition of the screws and nuts was determined using energy dispersive spectrometry (EDS) in a scanning electron microscope. The principal constituents of the reference hardware are listed in Table IV. We concluded based on the metallographic examination and chemical compositions that the alloy composing the reference screws is manganese-containing, low-carbon steel and is consistent with free-machining types of steel containing sulfur. The alloy composing the reference nuts is manganese-chromium alloy steel with fine grain structure, consistent with low-alloy steel such as 4140 in a normalized condition. The replacement screws are composed of an alloy with a grain structure similar to the reference screws, but the replacement nuts appear to be a completely different alloy than the reference nuts, which we have not identified.

TABLE IV – PRINCIPAL ALLOYING ELEMENTS

Hardware Item	*Manganese wt.%*	*Chromium wt.%*
Reference LWH Screw	1.0	-
Reference ACH Screw	0.9	-
Reference LWH Nut	1.2	1.1
Reference ACH Nut	1.2	1.1

Some key reference dimensions for the screw alloy microstructures are listed in Table V. The microstructure of the screws would be considered to be significantly different than the reference screws if any of the following features or conditions were observed:

- Absence of pearlite banding
- Absence of stringer inclusions
- Many elongated ferrite grains

- Cracks or voids in the ferrite grains
- Presence of other phases or microstructure features not present in the reference screws
- Average ferrite grain size less than 10 μm or greater than 15 μm
- Typical ferrite ASTM E112 grain size number greater than 10.5 or less than 8.5
- Typical pearlite band thickness greater than 5 μm
- Typical stringer inclusion thickness greater than 5 μm
- Typical density of stringer inclusions greater than 350 per square millimeter

TABLE V – KEY CHARACTERISTICS OF SCREW MICROSTRUCTURE

Characteristic	*Typical Values*
ASTM E112 Ferrite Grain Size Number	9.3 – 10.1
Average ferrite grain diameter	10 – 15 μm
Average pearlite band thickness	Less than 5 μm
Average stringer thickness	Less than 5 μm
Average stringer density	250 to 350 per square millimeter

The microstructures of nuts would be considered to be significantly different than the reference nuts if any of the following conditions are observed:

- Coarse pearlite grain structure
- Presence of large ferrite grains
- Presence of additional phases or microstructure features not present in the reference nuts

The polished cross sections of screws and nuts also were used to examine the threads and head slots. The reference hardware clearly are entirely *machined* from rod or bar stock, while the threads of the replacement screws and nuts clearly are manufactured by a *deformation* (rolling) process as indicated by the grain pattern distortions in Figure 6. However, the head slots of both reference and replacement screws are machined or ground, with no sign of grain distortion in the microstructures.

2.3 Hardness Tests on Polished Cross Sections

Rockwell hardness (*ASTM E18 Standard Test Methods for Rockwell Hardness of Metallic Materials*) was measured on the polished cross sections of the screws, and Vicker's microhardness (*ASTM E384*) measured on the polished cross sections of the nuts, as an easily obtained mechanical property. Vicker's was used on the nuts because the cross sectional surfaces are not large enough for Rockwell testing. The hardness results on the polished cross-sections are tabulated in Table VI. It was found that the hardness of the replacement screws and nuts are somewhat higher than the reference screws and nuts. For the recommended lot testing described in Section 3, we adopted the hardness of the reference screws and nuts, plus or minus three standard deviations, as the allowable range for average hardness. This is a generous range that should include any meaningful statistical variation of the reference screws. We note that the Rockwell hardness of the replacement screws is outside that reference range. Thus the Rockwell results would indicate that further testing should be undertaken on the replacement screws, as discussed in the Introduction and Section 3.

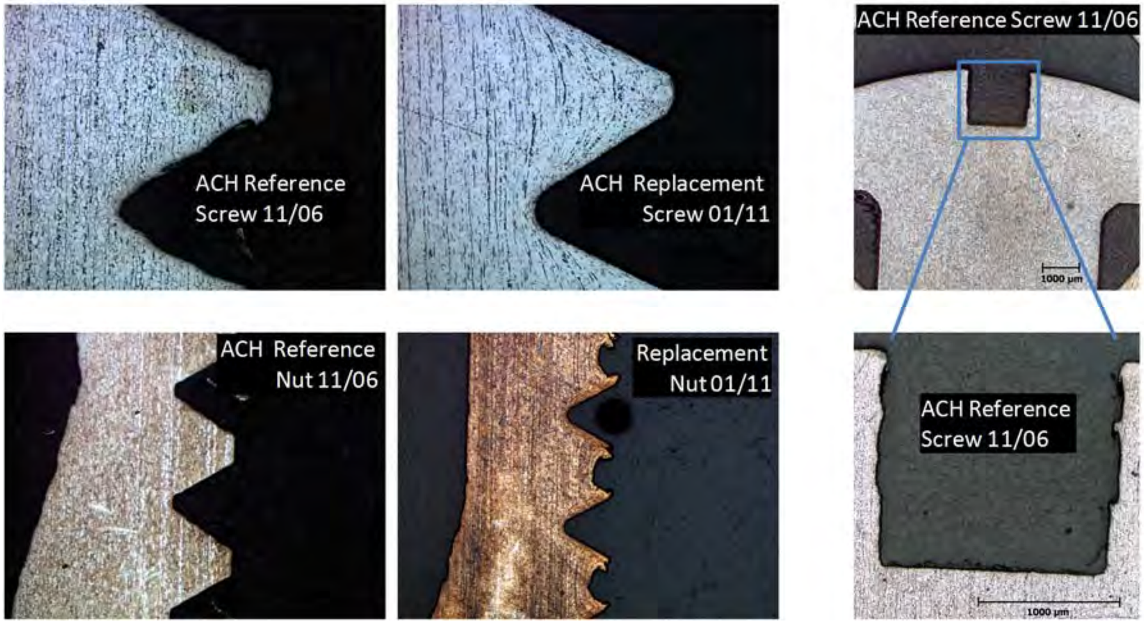

Figure 6. Typical screw and nut thread, and screw head slot, cross-sections. The grain distortions in the replacement hardware threads is an indicator of rolling as the manufacturing method. The lack of grain distortions of the threads in the reference screws, or the slot in the screw heads, indicates machining as the manufacturing process.

TABLE VI – CROSS-SECTIONAL HARDNESS

Hardware Item	*Rockwell Hardness*	*Vicker's Microhardness**
Reference LWH Screws	B 84 ± 1	195 ± 13
Reference ACH Screws	B 87 ± 1	209 ± 7
Replacement LWH Screws	B 93 ± 1	211 ± 9
Replacement ACH Screws	B 95 ± 1	208 ± 15
Reference LWH Nuts	-	255 ± 15
Reference ACH Nuts	-	277 ± 18
Replacement Nuts	-	230 ± 9

** 200 gram load, 15 second hold*

2.4 Tensile Tests

Tensile tests were devised to measure the strength of the screw and nut threads. We note that these are non-standard tests because there is not an ASTM standard that applies specifically to manufactured screws of this small size and configuration, primarily because of the difficulty of holding the test items, and insufficient shaft length to meet gage length requirements. However, *ASTM F606 Standard Test Methods for Determining the Mechanical Properties of Externally and Internally Threaded Fasteners, Washers, Direct Tension Indicators, and Rivets* provides the general context for our approach. The purpose of this test is to estimate an ultimate tensile strength of the screw material, and the force required to either strip the screw threads (or nut threads) or pull the nut through the chinstrap grommet. The test requires a fixture for holding the screws and a method of applying and measuring uniaxial force. The force may be applied by any convenient method that achieve a high enough force; for example, hydraulic load frames or screw driven tensile test machines that are commonly found in research and commercial mechanical testing labs. The test frame and load recording instrumentation must be capable of peak loads of at least 2000 lbf (pounds force). The NRL tests used an MTS servohydraulic load frame with a load cell calibrated to 4000 lbf.

A test fixture for holding the screws and nuts was machined, shown in Figure 7, and is similar in concept to the fixture shown in *ASTM F606*. Other configurations are possible. The requirement is simply that the screws and nuts be held securely in line with the load train, but separately so that the pieces can separate when the screw or threads fail.

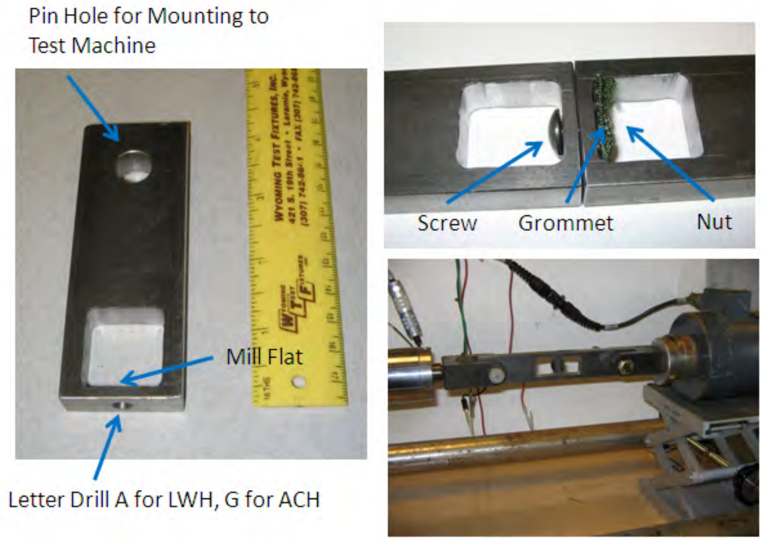

Figure 7. Fixturing used for the thread proof tests and tensile tests. For tensile tests of the screws, the grommet and conic nut is replaced with a machine nut. The lower right image shows the fixture as mounted in a horizontal servohydraulic test machine.

2.4.1 Screw/Grommet/Nut Proof Test and Thread Proof Test

For the thread pull strength test, a screw, nut and a chinstrap grommet are assembled in the test fixture. The test fixture is mounted in the load frame. Load is applied and increased or ramped (typically around 10 lbf per second) until a failure occurs. The type of failure that occurs and the load at which the failure occurs is recorded. Three types of failures could occur with this test: (1) the nut can pull through the grommet, (2) the threads of the screw can strip, or (3) the threads of the nut can strip. We observed no instances of the threads stripping from the conical nuts. The key results of the thread tests are tabulated in Table VII. Due to the limited supply of hardware available for testing, only a couple of tests could be done on each type of hardware.

Figure 8. Stripped threads of an LWH screw. The nut (on the right) threads are intact, and pieces of the screw threads are visible inside the nut

We observed that for all ACH screws, both reference and replacements, the conical nuts pulled through the chinstrap grommets rather than the threads stripping. The average load at which this occurred was 850 lbf, but the lowest value was 558 lbf. Thus, the fit of the conical nuts to the grommets is a key factor in such a failure. We note that the major diameters of the ACH nuts are essentially identical to the diameters of the LWH nuts, thus we attribute this nut pull-through failure to the grommets rather than the nuts. It was outside the scope of this project to define lot-testing options for grommets. The full screw/grommet/nut proof test described above indicates the proof strength of the configuration used in service. However, a proof test of only the screw/nut threaded connection strength would be more germane to the screw and nut thread strength alone. This can be measured by eliminating

Figure 9. An ACH screw/nut set that pulled through the grommet.

the possibility of the nut pulling through the grommet, by substituting a tight-fitting steel washer for the grommet.

For both reference and replacement LWH screws, the threads stripped from the screws at an average load of 1220 lbf, with a low value of 1052 lbf. For the recommendations for lot testing described in Section 3, we adopted the lowest measured values of thread stripping loads as the reference condition, including both the reference and replacement hardware results.

TABLE VII – SUMMARY OF THREAD PROOF TESTS

Type of Hardware	*Type of Failure*	*Failure Load [lbf]*
Reference LWH	Screw threads stripped	1231
Reference LWH	Screw threads stripped	1052
Replacement LWH	Screw threads stripped	1464
Replacement LWH	Screw threads stripped	1132
Reference ACH	Nut pulled through grommet	888
Reference ACH	Nut pulled through grommet	1062
Replacement ACH	Nut pulled through grommet	879
Replacement ACH	Nut pulled through grommet	558

2.4.2 Screw Tensile Strength Test

To obtain a provisional measurement of the screw material ultimate tensile strength, a section of the screw has to be reduced in diameter to ensure that the tensile load for failure is less than the screw/nut thread proof strength. Since this also is a non-standard test, we refer to the tensile strength obtained as “provisional”.

For this test, a tight fitting flat washer should be used instead of a grommet, or the conical nut should be replaced with a conventional steel hex nut, to support the necessary loads. For this test, the diameter of the screw shaft is reduced using a rounded end lathe tool, shown in Figure 10. This is necessary to reduce the failure load below the thread stripping load and to ensure that the tensile failure occurs in the center of the screw shaft. Other methods to create the reduced diameter may be used such grinding, provided that the cross-section is symmetrical and there are no sharp notches or corners present. We recommend that the radius of curvature at the thinnest diameter be no less than 1/16 inch, and the diameter of the thinned section be no less than 1/16 inch. The diameter of the thinned section must be recorded.

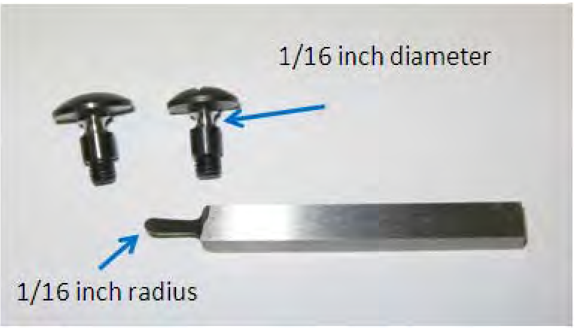

Figure 10. Sample preparation for the screw tensile strength tests. A rounded lathe tool bit is used to reduce the diameter of a region of the screw shoulders to about 1/16 inch.

The test procedure is to ramp up the load (about 10 lbf per second) until separation occurs. The load at which separation occurs is recorded. The provisional tensile strength is equal to the failure load divided by the cross sectional area of the thinned section at the location of the fracture.

Figure 11. Typical ductile fracture surface resulting from a screw tensile strength test.

Only two tests could be done on each lot of reference hardware due to limited number of samples available, but the results are all fairly consistent as shown in Table VIII. The average and standard deviation are composite values including both ACH and LWH screws of both the reference and replacement lot. We adopted a range of minus three standard deviations to plus three standard deviations of the observed reference screw values as the reference range for the recommended tensile test described in Section 3.

TABLE VIII – SUMMARY OF SCREW TENSILE STRENGTH TESTS

Type of Screw	*Tensile Strength* [psi]*
Reference LWH	102
Replacement LWH	113
Replacement LWH	101
Reference ACH	97
Replacement ACH	> 90**
Replacement ACH	107

** Provisional tensile strength / nonstandard test*
*** Threads stripped before screw broke*

2.5 Drop Weight Impact Test

ASTM standards exist for impact testing of metallic materials, primarily notched impact toughness testing, but there is no existing ASTM standard for impact testing of screw heads. Therefore, a non-standard impact test method was devised in order to create damage to the screw heads to give an indication of relative ability to survive impacts. These tests described below were not intended to mimic bullet impact on a helmet screw in realistic conditions. Rather, these tests are contrived to create readily observable metallurgical damage to the screws in laboratory conditions, for the purpose of establishing property and test methods for comparing batches of screws. Therefore we devised a test that yielded consistent quantitative results for an impact tolerance of the screws. Based on this test, we can recommend impact force parameters below which no significant damage should occur to the screws, and above which cracking, void formation and other damage occurs.

The tests were performed using a 5/8 inch diameter tool-steel striker in NRL's Instron Dynatup 9210 drop-weight impact tester. This instrument can record impact force and energy as a function of time during impact.

Our initial attempts to perform impact tests using screws mounted in Kevlar composite panels resulted in little damage to the screws, but a lot of damage to the panels. Based upon those initial trials, it was decided that in order to concentrate enough impact energy into the screw heads and obtain sufficiently high peak forces to cause cracks, a ¼ inch thick fiberglass (G-10 FR4) material would be used for substrate material. This material is stiffer and stronger than Kevlar panels, does not plastically deform (and therefore absorb energy), the properties are very consistent, it is relatively inexpensive, and the material easy to machine. The 4 inch x 4 inch panels of fiberglass were drilled with the appropriate sized holes for the LWH or ACH screws. The holes were slightly chamfered to remove the sharp edges that could contact the screw shoulder to head fillet. A base plate with a 2 inch diameter opening in the center for holding the panels in the test frame was fabricated. A schematic of the substrate configuration is shown in Figure 12 and the actual components are shown in Figure 13.

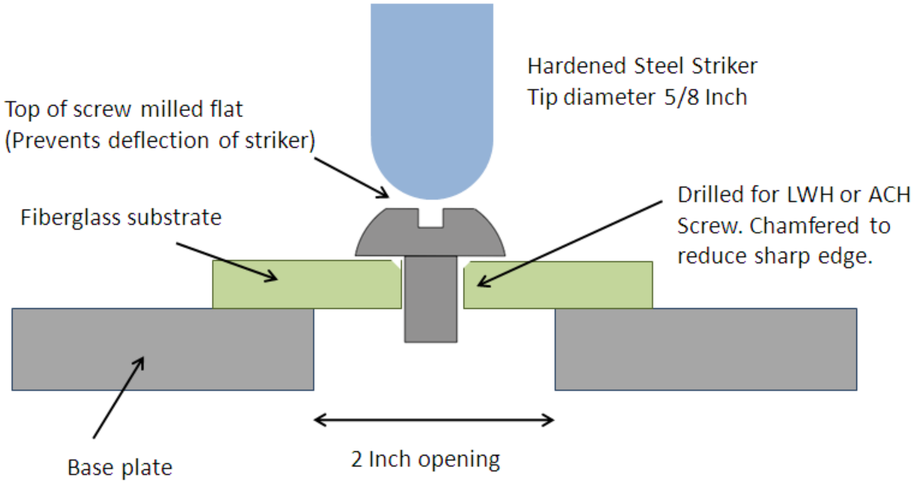

Figure 12. Schematic of the impact test configuration. The top of the screw was slightly flattened to prevent the rounded striker from deflecting. The substrate is ¼ inch thick fiberglass plate supported on a base plate of 5083 aluminum alloy.

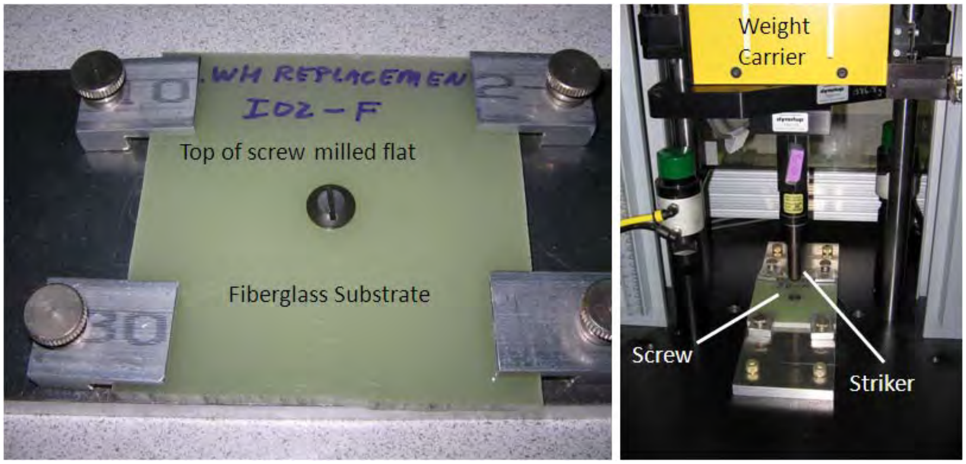

Figure 13. Close ups of a screw prepared for impact testing. The drop weight impact tester is an Instron Dynatup model 8100. Instrumentation in the striker holder measures the force of impact.

Approximately 0.015 inch was milled from the tops of the screw heads, creating a flat area about 0.30 inches diameter, to avoid problems with the striker being deflected by the rounded surface of the screw head. It would be preferable to use a flat-tipped striker so that the screw heads would not have to be altered, but such a hardened striker was not immediately available within the constrained time frame of this project. We note that the impact damage to the top of the screw heads, is entirely plastic deformation of the slot and top of the head, and is clearly compressive in nature. Tensile deformation associated with cracking and void formation occurs on the underside of the screw heads in the vicinity of the shoulder. Thus, we do not believe that the removal of 0.015 inches of material (about 12% of the total head height, but only a few percent of the volume of metal in the head) should significantly affect the impact loads for fracture.

Due to limited supply of reference screws, a series of tests were performed first on replacement screws to find the approximate impact parameters for the threshold above which cracking occurs, and below which damage is minimal. These tests were done by varying the peak impact force (by changing the drop height from 4 to 20 inches), with the same drop weight of 40 pounds. Impact energies ranged from 10 to 60 ft-lb (foot-pounds). These are low-speed impacts, ranging from 4.5 to 10 feet per second.

Once the impact damage threshold was found for the replacement screws, the same drop parameters were used to test a couple of reference screws and inspect for damage. As it turns out, the impact behavior of the reference and replacement screws was similar.

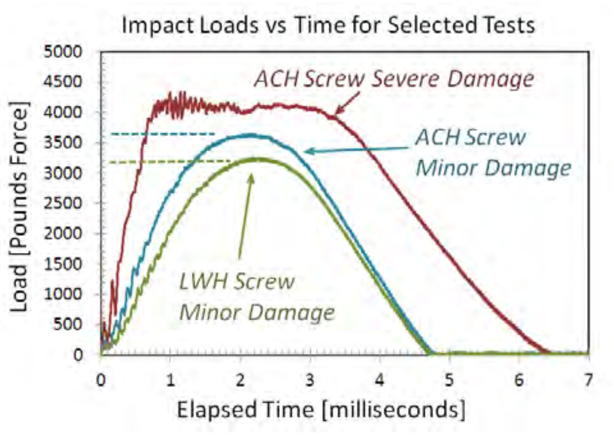

Figure 14. Some typical force versus time plots for drop weight impact tests

Figure 14 shows force versus time profiles for several typical tests. Peak forces with the 5/8 inch diameter striker are limited to about 4000 lbf by fracture of the fiberglass substrate, which is indicated by the flattening of the load-time curve. Tests at peak forces in this range (red curve) always resulted in severe damage to the screws, consisting of nearly complete shearing of the head from the shaft and usually with radial cracks in the head, as indicated in Figure 15.

Damage is detected first by visual observation of the screws, examining with a 10x magnifier. If large cracks are clearly visible, then the impact force is much higher than the threshold. If some surface damage is seen, but not necessarily large cracks, the screws should be cross-sectioned and polished in order to examine the internal microstructure in the region of the damage. Evidence of incipient damage indicating the peak impact force was close to the threshold are the observation of microscopic cracks, or groups of voids at the inclusions. Such damage, when it occurred, was always in the bottom of the screw head near the shoulder-head fillet. Figure 16 shows the polished cross sections of two screws, with areas of near-threshold incipient damage indicated.

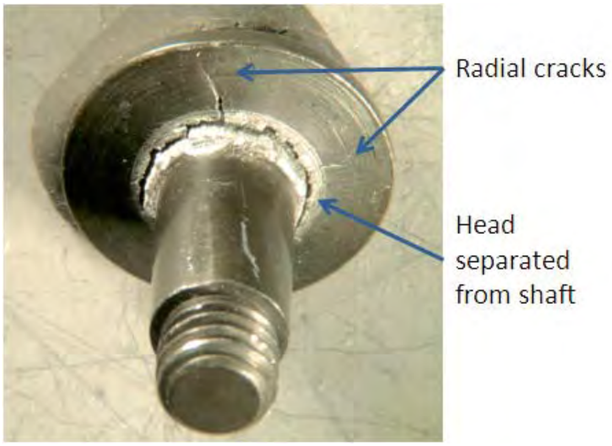

Figure 15. Example of severe damage inflicted by high force impact, showing circumferential cracking and radial cracking.

The peak impact force threshold for crack formation for NRL's test is nominally about 3,600 lbf for ACH screws, and about 3,200 lbf for LWH screws. Uncertainties in the impact load threshold values are about plus or minus 20%, due to the limited number of tests that could be done on reference hardware. The corresponding total impact energies were 18.7 and 12.7 ft-lb, respectively. These results are summarized in Table IX. The higher damage threshold of the ACH screws relative to the LWH screws is related

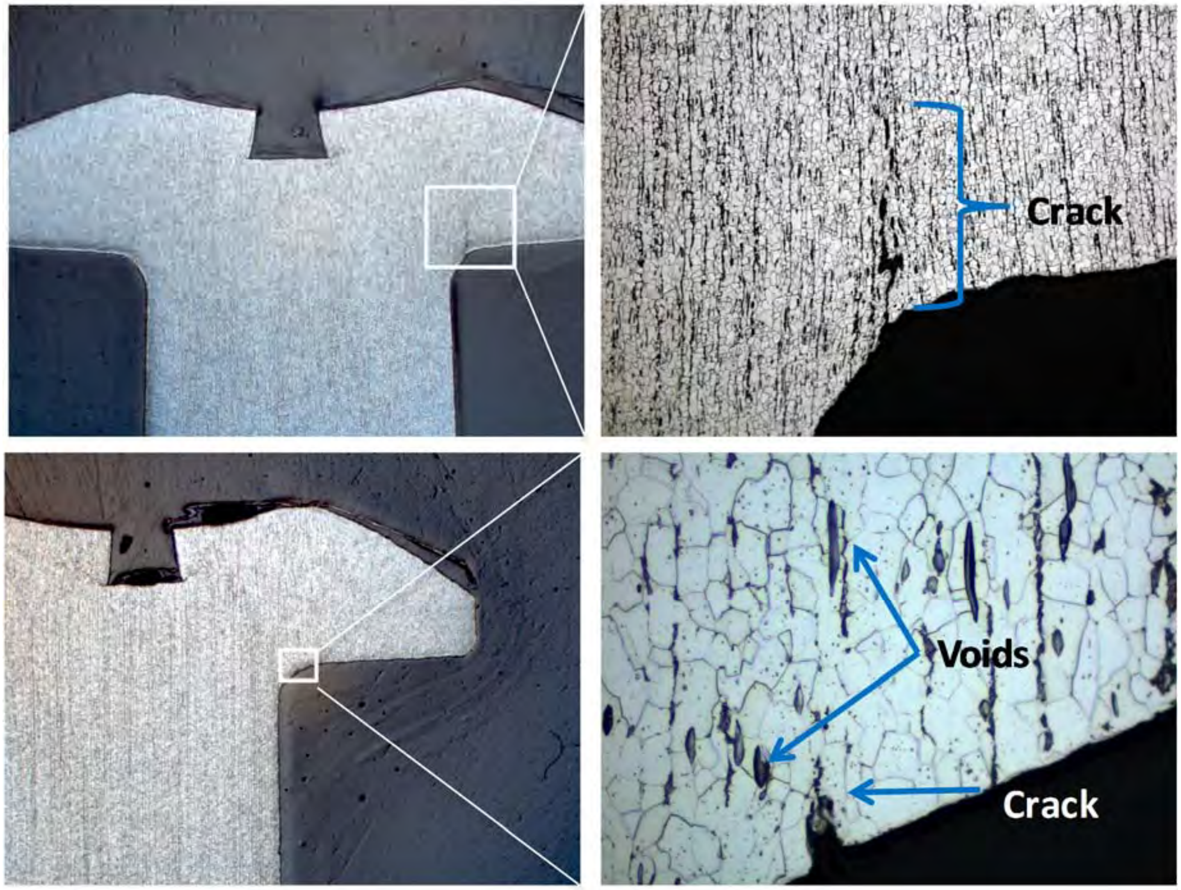

Figure 16. Examples of several kinds of microscopic damage due to impacts near the threshold for damage. Both cracks emanating from the bottom surface of the screw head are observed, as well as voids surrounding the sulfide stringers well into the interior of the material.

primarily to the area of the underside of the screw that supports most of the impact load. Although one might expect the difference to be due to the *area* of the head, in fact it appears to be related primarily to the *diameters* of the shoulder or head of the screws, rather than the areas. The ratio of impact threshold loads is approximately 3600/3200 ≈ 1.13. The ratio of the shoulder diameters is 0.245/0.216 ≈ 1.13 and the ratio of head diameters is 0.563/0.492 ≈ 1.14, both are very close to the ratio of observed impact force thresholds. For comparison, the ratio of head surface areas in contact with the substrate, equal to the head diameter squared minus hole diameter squared, times $\pi/4$, is 1.30, somewhat higher than the observed ratio of impact force thresholds.

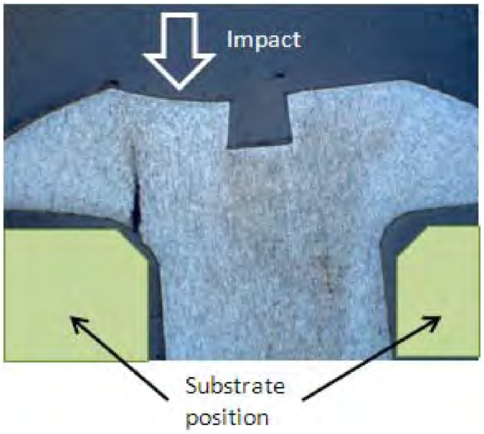

Figure 17. Example of cracking resulting from an off-center impact. In this case the peak impact force was the same as the damage threshold for centered impacts. This shows that off-center impacts are potentiall more damaging since the forces will be concentrated in a smaller area of support.

Figure 17 shows the result of an off-centered impact on an LWH screw at approximately the threshold peak force. The off-center impact cases relatively severe damage on one side but little damage on the other side. This same peak impact force, if centered, only causes microscopic damage (Figure 16).

TABLE IX – SUMMARY OF DROP WEIGHT IMPACT TESTS

Screw Type	*Drop Height [in]*	*Peak Impact Force [lbf]*	*Peak Impact Energy [ft-lb]*	*Visible Damage**
Replacement ACH	19.7	4342		Severe cracking both circumferential and radial
"	11.8	4211		Severe circumferential crack
"	7.9	3961		Partial circumferential crack
"	5.9	4083		Partial circumferential crack shear
"	3.9	3524		None visible
Reference ACH	5.9	3637		Possible circumferential crack
"	5.9	3800		Partial circumferential crack
Replacement LWH	7.9	3860		Severe circumferential crack
"	7.9	3821		Severe circumferential crack
"	3.9	3188		Possible circumferential crack
"	3.9	3324		Partial circumferential crack
"	3.9	3255		None visible
Reference LWH	3.9	3251		Possible circumferential crack
"	3.9	3200		None visible

** Damage to underside of screw head. All screws had severe deformation of the head and slot.*

We note that the relationship between impact energy and impact force is complex, depending on the striker, substrate, specimen mounting geometry, and drop height and weight. Although other types of impact tests are possible, NRL recommends a drop-weight test instrumented for measuring peak impact loads; i.e. similar to the test described above, to provide a direct quantitative measure of damage threshold for impact force or load. A non-instrumented drop weight test does not provide complete information about the impact, but could be used for qualitative comparison, using calculated impact energies In that case, the impact energy damage threshold should be at least 18.7 ft-lb for ACH screws and at least 12.7 ft-lb for LWH screws, assuming that the same striker diameter, same FR4 G10 substrate, and specimen mounting support dimensions are used. A non-instrumented test would be of more value if either some reference screws are available for comparison, or some test specimens are available that have been calibrated against NRL's instrumented drop test.

The degree of damage to screws obtained from helmets manufactured in 2006 (ACH) and 2009 (LWH), and replacement screws obtained from Gentex in January 2011 all appear to be very similar. These results indicate that this test approach, or some similar test approach, is suitable for comparing batches of screws; i.e., if a batch of screws has a substantially different cracking threshold or if the microscopic mechanism of damage is substantially different than the helmet screws tested in this project, it would not be expected to perform the same in service.

3. RECOMMENDATIONS FOR HARDWARE LOT EVALUATION

It is recommended that evaluation of new lots of helmet hardware proceed as described below. These main testing steps are shown schematically in Figures 18 for the screws and 19 for the nuts. The reference screws and nuts are the hardware removed from LWH helmets manufactured in April 2009 and ACH helmets manufactured in November 2006, described above and in Table I.

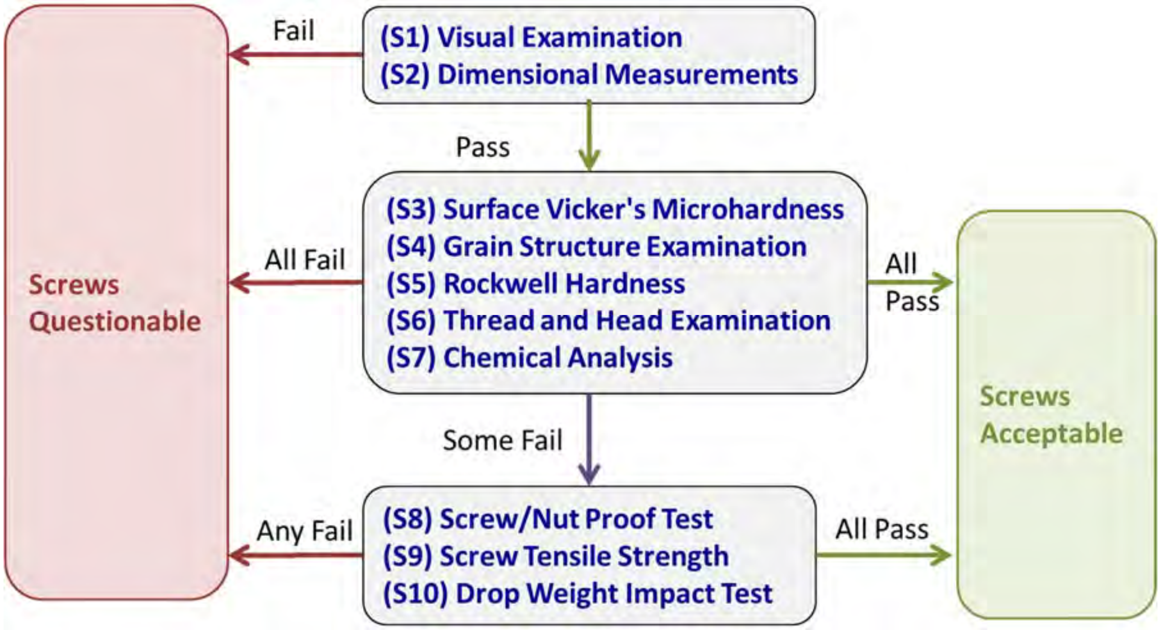

Figure 18. Recommended evaluation sequence for lot testing of screws.

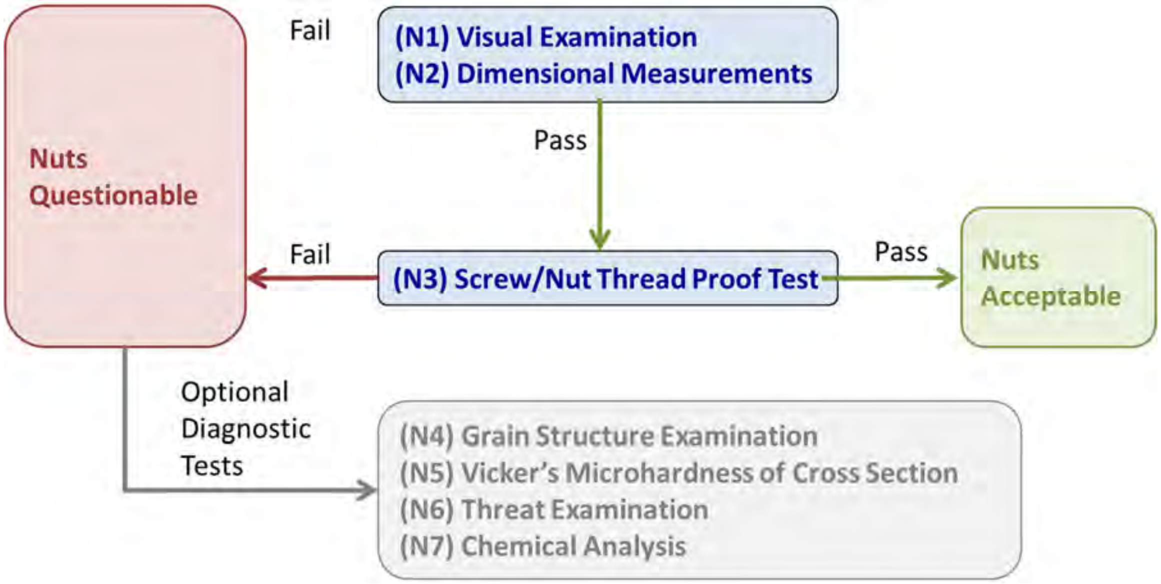

Figure 19. Recommended evaluation sequence for lot testing of nuts

We recommend that sample screws and nuts for testing be provided by vendors with each new batch of helmets using that lot of hardware, or with any new batches of replacement hardware. A minimum of 24 screws and 6 nuts should be allocated for the hardware tests described below.

Since the nuts are not subject to direct ballistic impact, the tests and criteria for nuts are different than for screws, and are described separately.

Tables X and XI summarize reference values or reference criteria for the screws and nuts, respectively. It should be noted that these ranges are based on limited statistical sample of the reference screws provided to NRL, but represent NRL's best estimate of reference properties at this time. The significance of the recommended ranges of property values could be improved with additional testing of reference hardware removed from approved lots of helmets, or by examining hardware that has been subjected to ballistic testing.

3.1 Evaluation of Screws

We recommend that tests (S1) through (S7), described below, are the minimal set of tests to perform on a batch of new screws. If these simpler tests (S1) through (S7) are consistent with the reference screw and nut properties in Table X and XI, then tests (S8) through (S10) are not necessarily required. However, to establish maximum confidence in the hardware, all tests described below should be performed.

3.1.1 (S1) Exterior Examination. The screws should be free of visible damage, burrs, scratches, and generally the exterior appearance similar to the reference screws described above. The corner between the head and shaft should be rounded, not square. The slot in the head should be centered. Threads should be well-formed.

3.1.2 (S2) Dimensional Measurements. Verify that the average key screw dimensions are compatible with the LWH and ACH reference screw dimensions listed in Table II. Measurements on six randomly selected pieces should be adequate, unless significant variations are noticed. Note that recommended maximum and minimum values are given in Table II only for the dimensions that NRL believes could directly affect the thread proof test or impact performance, based on the tests performed.

3.1.3 (S3) Surface Vicker's Microhardness. The surface Vicker's microhardness with a 50 gram load should be done on the sides of the screw shoulders. At least six indents per piece, and at least three pieces, should be sufficient to establish the typical behavior. The reference surface hardness of the screws is the range of 110 to 180 HV. If the average surface hardness is outside this range, then impact testing (S10) is recommended.

3.1.4 (S4) Grain Structure Examination. Using the procedures outlined in Section 2.2, examine the grain structure of several samples for similarity to the reference LWH and ACH screws. If the grain structure of the screws is significantly different than the reference screws, then thread/nut proof strength (S8), tensile strength (S9), and impact testing (S10) should be performed. Guidance for evaluating whether differences are significant is included in Section 2.2 of this report.

3.1.5 (S5) Rockwell Hardness of Screw Cross-Section. At least four Rockwell B scale indents should be made on the polished cross sections of at least three screws, well away from the edges and threads. These can be the same specimens as used for the metallographic examination. If the average Rockwell hardness is outside the range of B80 to B90, then tensile strength testing (S9) and impact testing (S10) is recommended.

3.1.6 (S6) Thread and Head Examination. Using the same cross-section samples as in (4), also examine the screw threads and the head slot for grain distortions and defects compared to the reference screws. If the screw threads are significantly different in appearance than the reference screws, then screw/nut thread proof testing (S8) is recommended. If there is grain distortion or defects around the screw head slot, or the fillet between head and shoulder, then impact testing (S10) is recommended.

3.1.7 (S7) Chemical Analysis. If the grain structure of the screws appears significantly different than the reference hardware, then chemical analysis is suggested to determine whether it is a different alloy composition. The analysis can be done by any convenient method, for example x-ray fluorescence or energy dispersive spectrometry in a scanning electron microscope, that is capable of determining approximate content of manganese and chromium and detecting any other major alloying elements. The principal composition of the reference screws is nominally 1% manganese with traces of other alloying elements detectable. If there are large differences of composition from the reference hardware, then tests (S8), (S9) and (S10) should be performed. We do not believe that precise chemical analysis of trace alloying elements is useful.

3.1.8 (S8) Screw/Nut Thread Proof Test. If there are significant differences indicated by any of the tests (S2), (S3), (S4), (S5), (S6), or (S7), above, this test is recommended. At least six sets of screws/nuts should be tested. The test method used by NRL for this project is described in Section 2.4.1 of this report. The proof strength for stripping of the threads from either the screws or nuts should be at least 1000 lbf for all tests. Note that this recommended minimum is based on a small statistical sample due to limited samples provided, such that a meaningful average and standard deviation of this property was not be determined. NRL recommends testing additional reference hardware to more clearly delineate the range of acceptable values.

3.1.9 (S9) Screw Tensile Strength. If tests (S4), (S5), or (S7) indicate significant differences of the test screws compared to the reference screws, then the tensile strength of the screw material should be measured using the procedure described in Section 2.4.2. At least six tests should be performed. The average provisional tensile strength based on the reference screws is in the range of 90,000 to 110,000 pounds per square inch (psi). Note that this recommended range is based on a small statistical sample, such that an average and standard deviation was not be determined. NRL recommends testing additional reference hardware to more clearly delineate the range of acceptable values.

3.1.10 (S10) Drop Weight Impact Test. If tests (S2), (S3), (S4), (S5), (S6) or (S7) indicate significant differences relative to the reference screws, then the drop weight impact test should be performed. The test developed by NRL is described in Section 2.5 of this report. Other impact tests are possible, but will have to be calibrated against reference screws that are known to be acceptable for service, or compared against NRL's test. Using the NRL test method, at least six screws should be available for testing. First, tests should be conducted with a peak impact force of about 3200 lbf for LWH screws and 3600 lbf for ACH screws, at least two screws each. The screws should be examined with a magnifier to detect any visible indications of cracking. If *severe* circumferential cracking is readily visible, or any radial cracking is present, with the 3200 or 3600 lbf impacts for LWH and ACH, respectively, then the impact resistance of the test screws is lower than that of the reference screws. In that case, additional tests at lower impact forces should be conducted to determine the threshold impact force. If cracks are not easily observed by visual inspection, then examination of polished cross sections by optical metallography should be used determine if any significant cracking or void formation occurred, as described in Section 2.5 of this report. If damage is limited to microscopic crack or void formation, then the impact resistance of the screws is similar to that of the reference screws. If no microscopic damage is seen then the impact force threshold is higher than that of the reference screws, and additional tests should be conducted at higher impact forces.

As with the tensile tests (S8 and S9), these impact criteria are based on very limited reference samples provided to NRL for testing, such that statistical significance could not be determined. NRL recommends additional reference hardware be tested. If any of the tests (S8), (S9), or (S10) yield degraded results compared to the reference hardware, then the hardware likely will exhibit reduced performance in the helmet application. It may then be necessary to either reject the hardware, or require the vendor to demonstrate that it passes ballistic tests.

TABLE X – SUMMARY OF REFERENCE VALUES FOR SCREWS

Test # in Text	*Test Description*	*Reference Values or Condition*
(S1)	Exterior Examination	Screws free of defects, burrs, scratches. Rounded fillet at head to shoulder corner, threads well-formed.
(S2)	Dimensional Measurements	See Table II
(S3)	Surface Vicker's Hardness	Screws 110 to 180 HV50
(S4)	Grain Structure	Similar to reference screws. See Section 2.2 for detailed criteria.
(S5)	Rockwell Hardness - Screws	Average between Rockwell B80 and B90
(S6)	Thread and Head Examination	No grain structure distortions in head, area around head slot or shoulder to head transition. Free of cracks, voids, notches, other defects.
(S7)	Chemical Analysis	Low-carbon steel with nominal 1% Mn Traces of other elements can be present
(S8)	Screw/ Nut Thread Proof Test	At least 1000 lbf to strip threads from screws. No stripping of nut threads.
(S9)	Screw Tensile Strength	Between 90,000 to 110,000 psi
(S10)	Drop Weight Impact Test	Per NRL test method described herein: Minor damage for impact peak force of 3,200 lbf to LWH screw heads; or 3,600 lbf to ACH screw heads.

3.2 Evaluation of Nuts

Since the nuts are not subject to direct ballistic impact, the evaluation of the nuts can be limited to the three basic tests described below.

3.2.1 (N1) Exterior Examination. The nuts should be free of visible damage, burrs, scratches, coating or surface treatment delamination, and generally the exterior appearance should be similar to the reference nuts described above. The screwdriver slot in the nut should be centered and free of burrs. Threads should be well formed.

3.2.2 (N2) Dimensional Measurements. Verify that the average key nut dimensions are compatible with the reference nut dimensions listed in Table II. Measurements on six randomly selected pieces should be adequate, unless significant variations are noticed. Note that the recommended maximum and minimum values in Table II are listed only for the dimensions that NRL believes could directly affect the thread proof test.

3.2.3 (N3) Screw/Nut Thread Proof Test. A simple proof test method similar to the screw tensile test is described in Section 2.4.1. At least three sets of screws/ nuts should be performed. If testing includes chinstrap grommets, the proof strength for nuts pulling through the grommets should be at least 500 lbf to be comparable to the reference hardware. The proof strength for stripping of the threads from either the screws or nuts should be at least 1000 lbf for all tests. (Note that these recommended minimums are based on a small statistical sample). No stripping of the nut threads was observed in our evaluation of the reference hardware, therefore if this occurs it would be considered anomalous.

NRL suggests that the proof test is a sufficient indicator of the characteristics of the conical nuts. However, if additional evaluation of nuts is desired, for example to determine if they are similar materials properties to the reference nuts, or if the proof strengths are below the reference range and some indication of the reason is sought, or if the proof test is not available, then several optional tests are suggested.

3.2.4 (N4) Grain Structure Examination. Using the procedures and reference criteria outlined in Section 2.2, examine the grain structure of the nut material for differences from the reference nut material.

3.2.5 (N5) Vicker's Microhardness of Nut Cross Section. Conduct a minimum of six indents in the vicinity of the nut threads of at least three nuts, using a load of 200 grams. These can be the same specimens used for metallographic examination. The average Vicker's microhardness of the reference nuts is in the range of 210 to 330 HV.

3.2.6 (N6) Thread Examination. Using the same cross-section samples as in (N5), also examine the nut threads for grain structure distortions, defects, or malformations, as compared to the reference nuts.

3.2.7 (N7) Chemical Analysis. The analysis can be done by any convenient method, for example x-ray fluorescence or energy dispersive spectrometry in a scanning electron microscope, that is capable of determining approximate content of manganese and chromium and detecting any other major alloying elements. The principal composition of the references nuts is nominally 1% manganese and 1% Cr with traces of other alloying elements detectable.

TABLE XI – SUMMARY OF REFERENCE VALUES FOR NUTS

Test # in Text	*Test Description*	*Reference Values or Condition*
(N1)	Exterior Examination	Nuts free of defects, burrs, scratches, etc. Threads well-formed.
(N2)	Dimensional Measurements	See Table II
(N3)	Screw/ Nut Thread Proof Test	At least 1000 lbf to strip threads from screws. No stripping of nut threads.
(N4)*	Grain Structure	Similar to reference nuts. See Section 2.2 for criteria.
(N5)*	Vicker's Microhardness – Nuts	Average between 210 to 330 HV200
(N6)*	Thread Examination	No grain structure distortions. Free of cracks, voids, notches, malformations.
(N7)*	Chemical Analysis	Nuts nominally 1% Mn and 1% Cr Traces of other elements can be present

**These tests are optional but recommended*

4. ADDITIONAL RECOMMENDATIONS

NRL also recommends that four additional follow-on studies be done:

(a) Conduct the testing described in this report on additional samples of hardware removed from helmets that have passed ballistic testing, or on a lot of replacement screws that are deemed to be acceptable. This will allow more definitive and statistically significant range of reference values for the various tests, particularly the tensile and impact tests. A minimum additional 24 screws and 6 nuts of each type should be tested, six each for thread proof test and screw tensile test, and 12 for drop weight impact testing.

(b) Develop a standardized laboratory impact test for testing of screws heads. The instrumented NRL drop-weight test described in Section 3, which provides a measure of impact force, can form the basis of such a quantitative test. However, a number of variables (for example, impact velocity, drop weight, thickness and size of substrate, striker form and dimensions) need to be studied further to create a practical specification for testing and provide a basis for inter-laboratory standardization.

(c) Examine hardware that has been subjected to actual ballistic testing, including both screws that have remained intact as well as hardware that has fractured. Such examination will identify failure mechanisms as well as define ranges of unacceptable properties.

(d) Identify better alloys for the helmet hardware application that are less susceptible to fracture due to ballistic impacts. Specifically, NRL recommends testing alloys that do not have the stringers described in Section 2, above, because as the impact testing showed, those stringers are the sites of void formation that contribute to failure.

5. ACKNOWLEDGEMENTS

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