THE APPLICATION OF SBIR WATER IMPACT RESULTS TO DESIGN CRITERIA

Gil Wittlin and Max Gamon (DRI)
Steve Soltis and Timothy Smith (FAA)

ABSTRACT

The results of a comprehensive Small Business Innovative Research (SBIR) Program sponsored by NAWCAD and the FAA are described with regard to two key questions related to the validity and the application of the results. Hybrid and FEM modeling results are shown. Full Scale water impact testing results are included. Current ditching and water impact compliance procedures are shown to be limited. Comparisons between test and analysis results and trends show that analytical techniques can address civil and military ditching/water impact design considerations. The current KRASH hybrid analysis technique is shown to be capable of developing water impact design limit criteria for FAR 27/29 aircraft. A preliminary set of Design Limit Envelopes (DLE) are presented, along with a discussion of those parameters that affect the envelopes.

BACKGROUND

The SBIR is a comprehensive three phase analysis and test program and design application program consisting of;

1. Phase I - An evaluation of analytical tools and available scale model ditching and water impact test or accident data (Hybrid-KRASH and FEM-DYTRAN)
2. Phase II -The performance of 2 full-scale fully instrumented helicopter water impacts along with both hybrid and FEM modeling/correlation.
3. Phase III - The application of results to develop Design Limit Envelopes (DLE) for ditching and water impact.

Figure 1 shows:

- Existing survivable envelopes as determined from accident data
- The impact conditions for the two SBIR tests designated S1 and S2
- The ditching environment and the range of analysis performed with regard to the ditching condition, high sink speed, and high forward velocity accidents

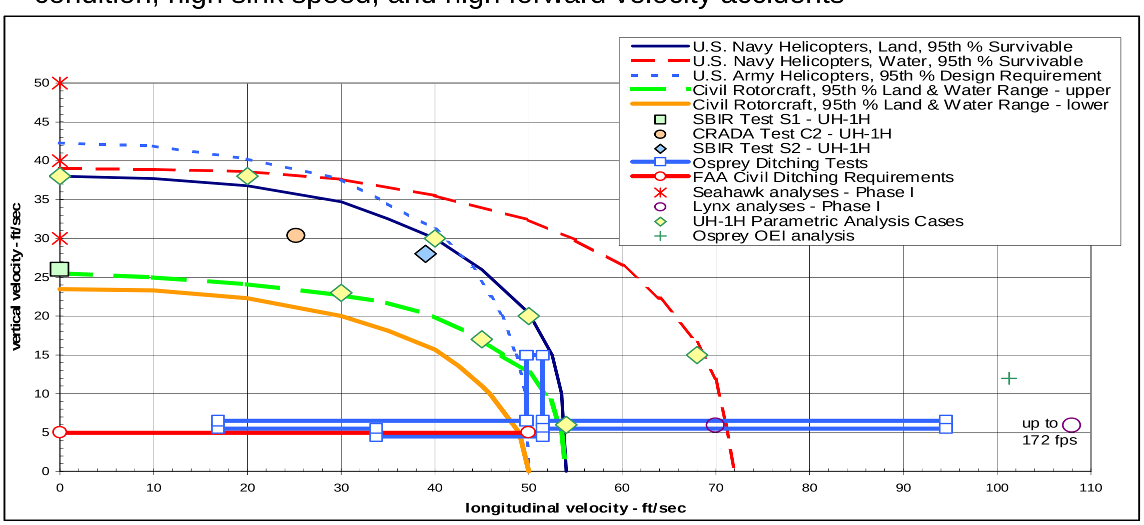


Figure 1 Accident Crash Survivable Envelopes and SBIR Tests and Analysis

S1 Vertical Impact S2 Combined Vertical-Longitudinal Impact

Figure 2 Water Impact Test Conditions

The first test in Figure 2, designated S1, was an impact at 26 fps vertical, 0 fps longitudinal, and 0 degree pitch with a truncated UH-1H airframe. The second test in Figure 2, designated S2, had impact conditions of 28 fps vertical, 39 fps longitudinal, and 4 degrees nose-up pitch, using a full UH-1H aircraft with tail section and landing skids.

SIGNIFICANCE OF SBIR RESULTS

To fully assess the significance of the SBIR results one has to evaluate the various task results in relationship to how the information can best be used by the DOD, DOT and industry. In order to assess the validity of the SBIR results, two fundamental questions are addressed. They are;

1. Can analytical modeling accurately simulate or represent the significant aspects of full-scale water impact and scale-model ditching tests?
2. Can analytical modeling be an effective tool for the development of crash design evaluation and criteria, and if so how?

Analytical Modeling Simulation of Full-scale Water Impact and Scale Model Ditching Tests

There are three aspects of the test and the corresponding analyses; kinematic behavior, average responses, and discrete responses that have to be examined.

In the first category one has to consider if the analysis correctly depicts airframe behavior upon initial impact and subsequent motion. The analysis does indeed show appropriate kinematic behavior with regard to appropriate impact times and post-impact behavior compared to that experienced during pure vertical impact and combined vertical-longitudinal water impact and ditching tests.

- Pitch attitude.

1. For the S2 test, the test specimen hits the water with a 4-degree nose-up attitude and thereafter maintains that attitude or pitches more nose-up, prior to taking on water and sinking. The vehicle pitch attitude from the KRASH simulation of test S2 shows that the aircraft impacts the water at 4-degrees ANU, stays that way for about 10 msec., then gradually increases to + 6-degrees. It maintains that attitude for another 15 msec. And then pitches further nose-up to 8 degrees. This behavior is in agreement with the test results for about 100 msec. after impact, at which time flooding occurs.

2. During the Phase I effort, the ditching sequence comparison of the Osprey for test and analysis (DRI/KRASH) shows that the peak pressures and the sequence of events are in agreement between the test and analysis. Table 1 shows the comparison.

Table 1 Comparison of Ditching Kinematics Behavior

	Peak pressure (psi) at time (sec)		Initial contact of FS after impact (sec)	
Location	**Analysis**	**Test**	**Analysis**	**Test**
FS 552 – 576	2.6 (0.050)	3.0 (0.018)	0.000	0.000
	-	-7.0 (0.072)	-	-
FS 532	16.2 (0.070	18.0 (0.050)	0.020	0.033
	16.4 (0.100)	-	-	-
FS 486	19.7 (0.390)	20.0 (0.136)	0.110	0.108
FS 380 – 386	17.2 (0.490)	14.0 (0.430)	0.410	0.380

- Vehicle overall cg accelerations:

1. In the SBIR water vertical impact test (S1) test the agreement between test and analysis (Reference 1) was noted for both pretest posttest analyses. The post-test analysis showed that the following kinematic behavior agreement between analysis and test was achieved for the post-test modeling that best represented the test specimen and condition.

Cg vertical acceleration ------- -6.9 %	overall acceleration-------- 9.5 %
Water penetration -------------- -8.3 %	overall pressure ----------- - 8.2 %
Cg velocity change ---------- -18.9 %	

Individually closer agreement of some parameters could be achieved, but at the expense of agreement with other parameters.

2. For the S2 test only pretest analysis was performed and the agreement between analysis and test showed the following;

Cg longitudinal acceleration---- 8.3 %
Cg vertical acceleration--------- 17.6 %

- Floor pulse

Table 2 notes the current seat dynamic test floor pulse requirements for civil and military rotorcraft.

Table 2 Civil and Military Seat Dynamic Test Requirements

LOCATION	FAR27/29 P27/29.562 26 fps vertical 15 fps longit.	U.S. Army Survival Guide 36 fps vertical 21 fps long.	
	dynamic condition	min. req't	
		cockpit	cabin
Floor pulse			
vertical accel - g	26	44	32
rise time, sec.	0.031	0.043	0.059
onset rate, g/sec.	967	1027	542

These are idealized triangular pulses with a specified peak g, onset rate and duration. Everyone recognizes that these pulses do not take into account specific aircraft fuselage station floor locations (other than possibly pilot or cabin, as in the case of U.S. Army seat pulses), aircraft weight or size considerations, or specific design characteristics. Thus, when one assesses the SBIR simulation results, the end objective of the agencies has to be borne in mind. To that extent the analysis does depict the characteristic response required by the agencies. This is illustrated as follows:

1. The comparison of idealized triangular floor vertical pulses obtained from approximately fifteen (15) S1 test measurements , 11 of which are on the floor, is shown in Figure 3.

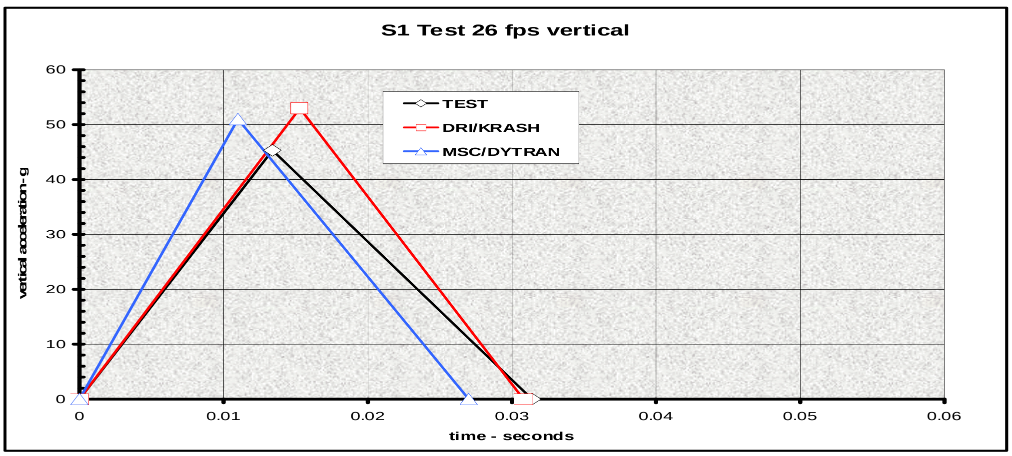


Figure 3- S1 Test and Analysis Floor Pulses

It can be observed that the analyses show peaks that differ from the test peak by approximately 10 % to 17 %. The rise times are sharp for the test and analyses and range from approximately .011 to .015 seconds. More importantly, the test and analysis results are in agreement in that water impact floor pulses have significantly shorter rise times than floor pulses associated with rigid ground impacts. The onset range for the S1 test is 3500 g/sec. to 4500 g/sec. This result is consistent with the body of data presented in Figure 4**,** which shows that water impact data is generally in the range of 3000 g/sec. to 4670 g/sec. It is also important to recognize that floor pulse onset rate data for ground impacts is in the range of 540 g/sec. to 1450 g/sec., and the regulations are around 1000 g/sec. Thus, the real significance of the SBIR test and analysis, other than their being in agreement, is that the water impact pulse characteristics have to be considered in light of current seat test requirements. It has been shown that a four-fold increase in onset rate can result in lumbar loads increasing 25 %.

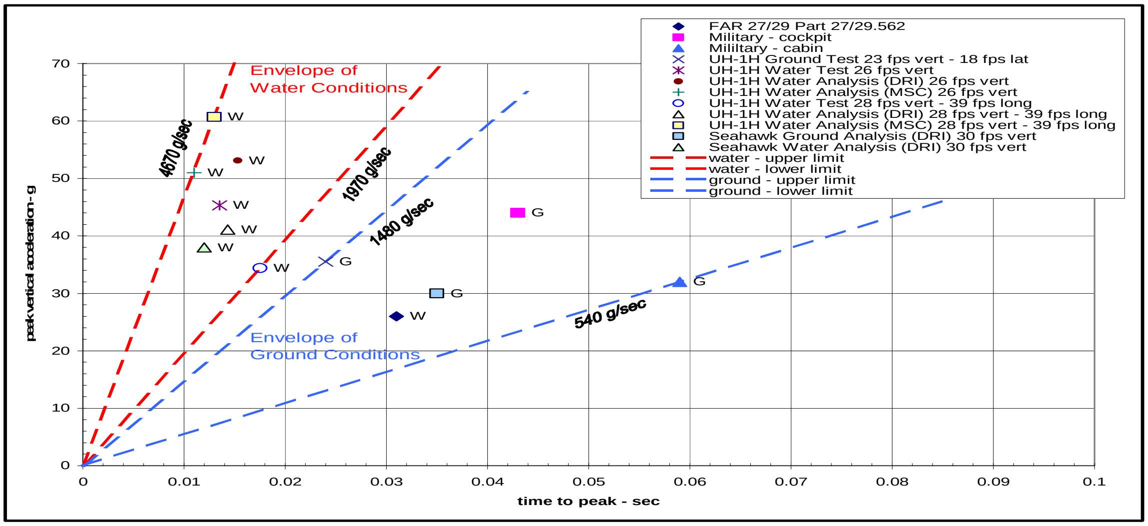


Figure 4 Floor Pulses-Water Versus Rigid Ground Vs. Seat Dynamic Tests

2. The longitudinal pulse can only be obtained from the S2 test. Because 9 of the 10 floor measurements were on slabs, the results tend to indicate lower response levels than exist on the floor, and thus should not be considered with regard to design. What is significant is that there are two characteristic pulses associated with the longitudinal impact. The first is a primary floor pulse that occurs during the early stage of the impact, along with the initial vertical pulses. Since it takes a relatively long time to arrest the forward velocity of the aircraft, there is also a long term pulse as depicted by the cg pulse. The short term primary pulse is associated with a very short duration and small velocity change. The analysis prediction of the cg pulse is shown in Figure 5.

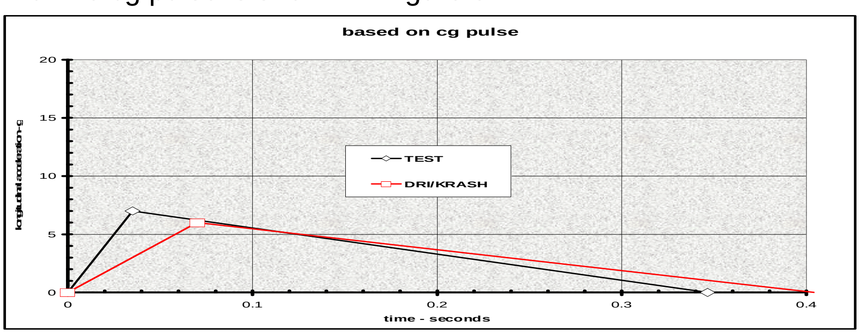


Figure 5 –S2 CG Longitudinal Pulse

- <u>Panel average pressure</u>

1. S1 test results illustrate that analysis can predict average panel pressure within <u>10 %</u> of the corresponding test result.
2. S2 results illustrate that with pretest-only analysis the average panel pressure can be predicted within <u>4 %</u> of the corresponding test result. Also that panel failures were predicted

with approximately 80-90 % agreement with the test with regard to specific locations.

- Floor average vertical and longitudinal accelerations

1. S1 test results illustrate that the floor average vertical acceleration can be predicted within 8 % of the corresponding test result.
2. S2 test results show that the floor vertical average acceleration pretest prediction is 23 % higher than the corresponding test data.
3. The S2 test results show that the floor longitudinal acceleration pretest prediction is 13% lower than the corresponding test data at the one floor location (non-slab location).

- Panel damage and failure

1. S1 and S2 results illustrate that the analysis can predict panel failures with 80-90 % agreement with test data with regard to specific locations and taking into account a multitude of different panel materials, designs, and sizes.
2. The analysis results at times can provide a more consistent assessment of the responses than the measured test data. Figure 6 shows severe damage and failure of centerline panels from FS 60 and aft, and the measured versus analytically determined pressures at FS 139. The analysis shows pressures reaching failure levels, wherein the measured data does not.

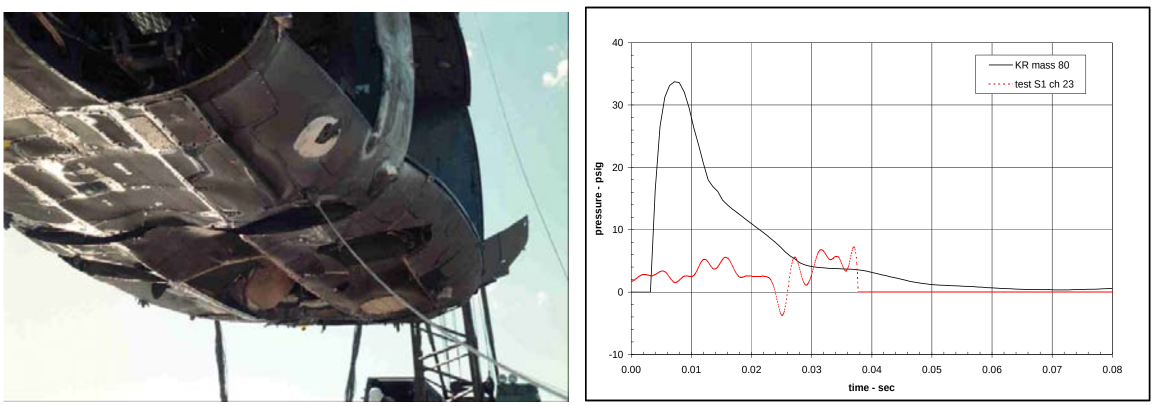


Figure 6 – S1 Fuselage Damage and Response

The third aspect of simulation of test data deals with the ability to determine precise response curves at each and every location. While one may consider it desirable to have an exact reproduction, including every nuance of the shape of the response, it is not possible, nor practical with about 100 measurements (pressure, acceleration, panel damage) to correlate. Nor is it necessary when one considers the FAA and U.S. Navy goals. Both the test measurements and the analytical representations are dependent on detailed mass distributions and locations that are assumed or estimated and not always known. For example, during the S1 test, 11 of the 15 vertical floor responses were measured on mass slabs. In the S2 test only 1 of the 10 vertical floor accelerations were measured on a mass slab. The difference between measuring on a slab versus measuring on a lighter weight structure is dramatic in both response peak and shape. The analysis does adequately predict the response characteristics as is noted in the following illustrations:

- Pressure response characteristics

A comparison of pressure responses from the S1 and S2 test is shown in Figure 7 . For the curves shown it can be observed that the peak value, time at which the peak occurs, the rise time to the peak and the overall shape are consistent. However, the curves do not match exactly in every aspect, nor does every location show as good a representation.

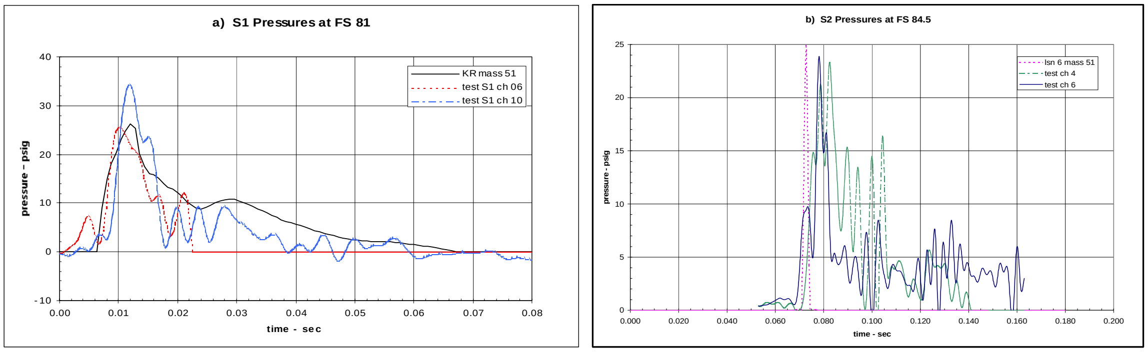


Figure 7 –S1 and S2 Pressures

- <u>Acceleration Response Characteristics</u>

1. A comparison of acceleration responses from the S1 test , shown in Figure 8, point out that neither the test nor the analysis displays what one would describe as a purely triangular pulse. Thus, one has to approximate an appropriate rise time and peak. This was done for the S1 test and the results, noted in the previous discussion on floor pulses, indicated basic agreement between analysis and test for an idealized triangular pulse with regard to peak g, rise time and duration.

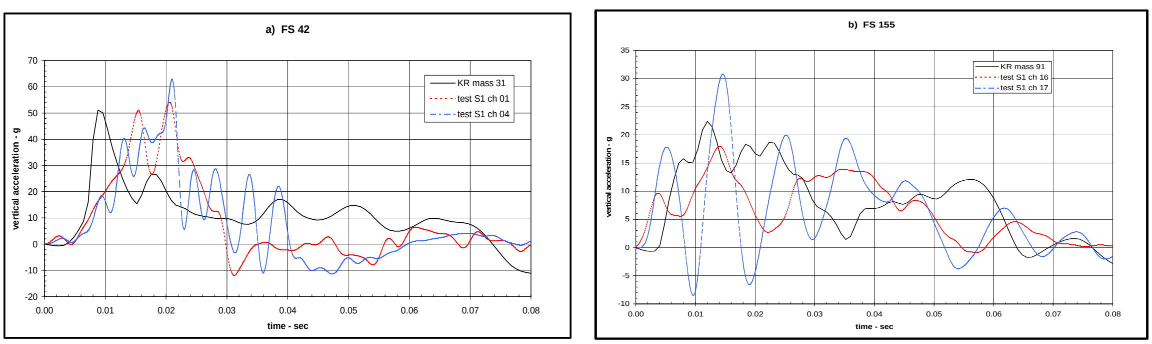
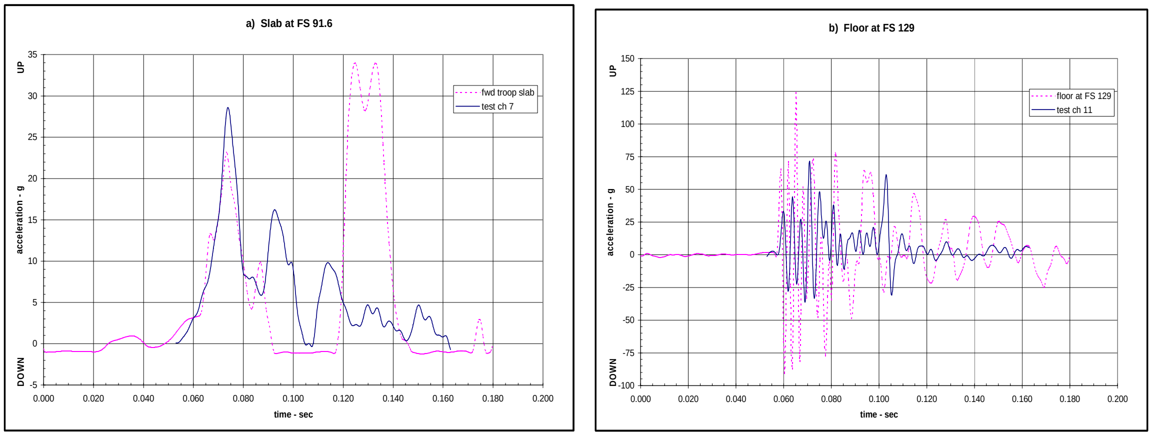


Figure 8- S1 Acceleration

2. A comparison of acceleration responses from the S2 test is shown in Figure 9. This comparison was more difficult to characterize. For example, the pulse shown in Figure 9a is based on a slab mass response. The analysis indicated a second pulse acting on the floor after the underside panel failed. Most likely this is an over-estimation of what occurred. On the other hand the analysis did not provide for slab restraint failures, which were noted to have occurred. If not for the secondary pulse, the analysis would show good agreement with test data.

   The pulses shown in Figure 9b are based on a floor response. The oscillatory nature of the lightweight structure response is represented in both the analysis and test data. Albeit the peaks are substantially different, the characteristic response is the same.

When lightweight structures are involved, the response will be sensitive to the assumed mass in the model or to the effective mass that participates in the test measurement. This type of sensitivity supports the value for overall averages as opposed to a strong dependence on discrete comparisons.



(a) (b)

Figure 9 –S2 Accelerations

- Discrete location comparisons

The summarized data is provided in Table 3. At best agreement is at 58 % with regard to peak value and around 80 % with regard to time of occurrence.

Table 3 Discrete Location Test and Analysis Comparisons

S1 TEST - 26 FPS VERTICAL

	percent agreement with test data			
	DRI/KRASH		MSC/DYTRAN	
	PEAK	TIME	PEAK	TIME
PRESSURE	40.6	62.5	23.3	83.3
ACCELERATION	50.0	77.8	25.0	76.9

S2 TEST - 28 FPS VERTICAL, 39 FPS LONGITUDINAL

	percent agreement with test data			
	DRI/KRASH		MSC/DYTRAN	
	PEAK	TIME	PEAK	TIME
PRESSURE	47.4	63.2	7.1	71.4
ACCELERATION	58.1	48.4	30.0	35.0

The SBIR Osprey scale model ditching comparisons, shown in Figure 10 reveal that the peak pressures agree with peak test measured pressures at fuselage design stations within -2.5 % (FS 486) to -10.8 % (FS 532). At the non-design critical fuselage stations where the pressures were much lower (2 to 3 psi), the agreement was within +25 % (FS 380) to –33.3 % (FS 576). i.

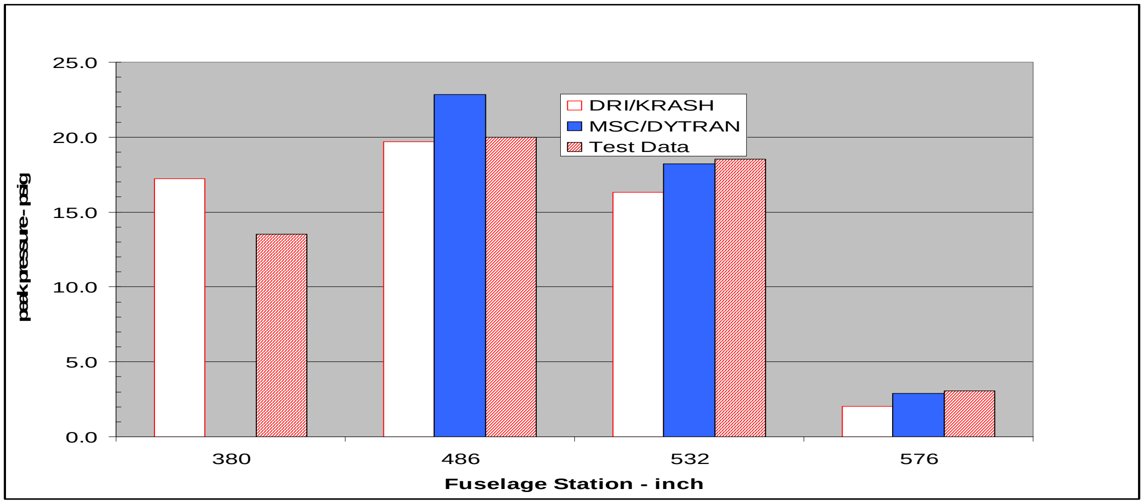


Figure 10 - Comparison of Analysis Pressure Results with Osprey Scale Model Tests

<u>Analytical Modeling as an Effective Tool for the Development of Crash Design Evaluation and Criteria</u>

To determine the potential effectiveness of analytical modeling one has to determine the goal of the agencies and industry. If it is to determine whether current criteria are adequate for future aircraft, then testing alone will never achieve that goal. Everyone understands the limits in testing; namely scope and cost. The SBIR results also show that test data is not infallible and analysis is a good backup to help understand the airframe behavior. The analysis presented in this SBIR does demonstrate how the modeling can be an effective tool to assist in the development of design criteria, and if necessary design concepts. To emphasize this point several illustrations are presented:

- <u>Trends</u>

1. The application of KRASH to Osprey ditching results allows for how different trends for a wide range of ditching parameters can be realistically determined. One such example is provided in Figure 11.

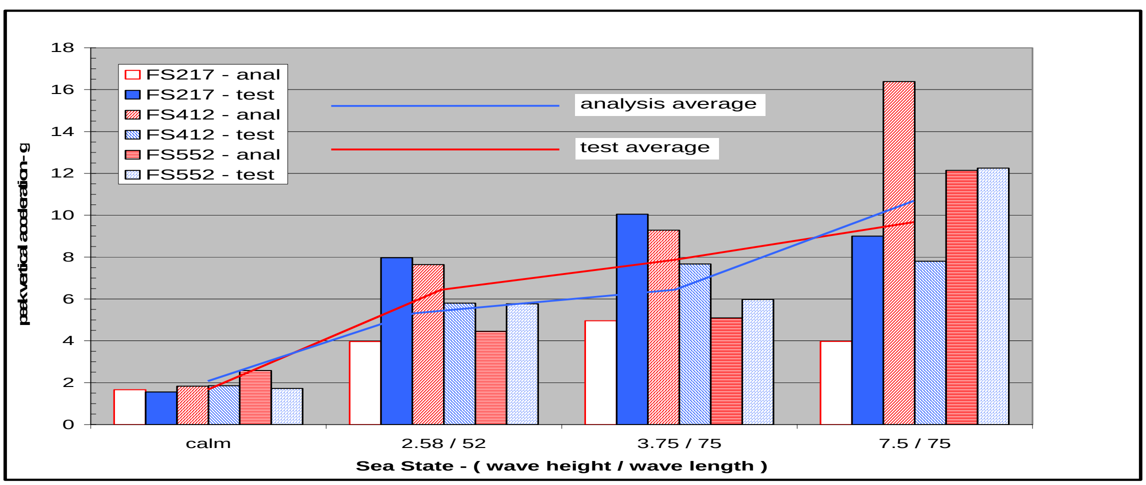


Figure 11-Comparison of Sea State VS. Calm Seas- Osprey Test and DRI/KRASH Analysis

2. The SBIR analyses demonstrated the wide range of aircraft configurations and impact conditions that can be analyzed with the hybrid model, because of efficient execution time and features. The SBIR demonstrated the capability to model rotary wing aircraft in the range of 10,000 to- 20,000-to 46,000 GTOW. The SBIR demonstrated the capability to

model accident conditions up to 160 knots forward velocity, as well as high sink speeds up to 60 ft/sec and combinations in between. Helicopter configurations include the Lynx, Seahawk and UH-1H.

3. The SBIR demonstrated the ability to rationally depict trends between the S1 and S2 test conditions with regard to acceleration response, pressure response and transfer functions relating acceleration to pressure at several floor regions. The pressure trend is presented in Figure 12 and discussed as well.

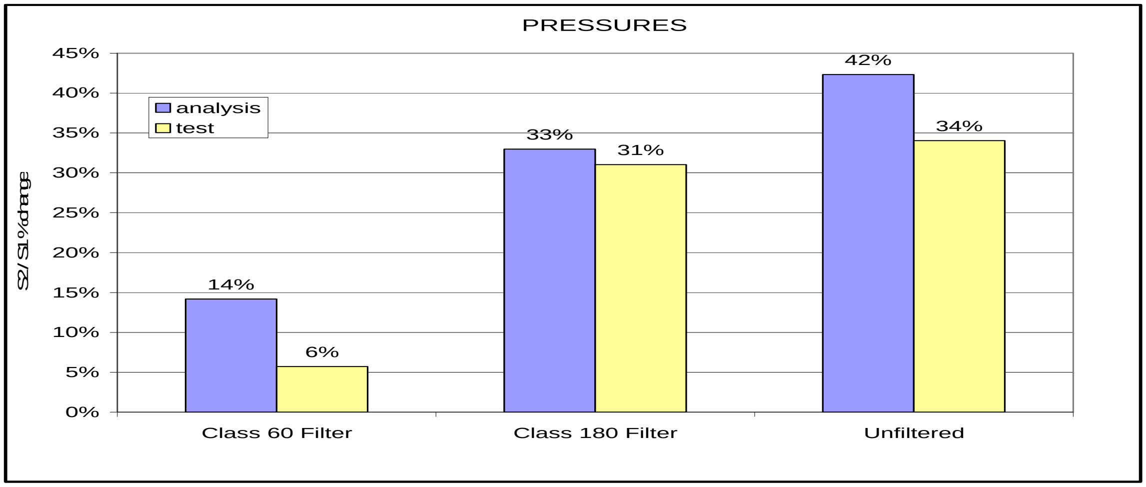


Figure 12 Pressure Trends; S2 VS. S1

The trend is presented for 3 filter comparisons, although unfiltered or SAE class 180 is more representative of panel pressure design data. All the filter comparisons (Figure 11) for the underside panel pressures show positive or increased pressures for the more severe S2 test. For the test results this ranges from +6 % for the class 60 filter to +34 % for the unfiltered data. The analysis ranges from +14 % to +42 % for similar comparisons. The increases, with regard to expected increases, are not nearly as large as one expect from the magnitude of velocity increase from S1 to S2 (factor of 1.85). The rationale for why the measured and predicted increases are not as large as anticipated, based on velocity increase, is as follows:

- The S1 test resulted in many panels achieving pressure levels near, at or above the design failure design pressures.
- The S2 test, while definitely much more severe than S1 resultant as noted by the additional panel failures, can not produce higher underside panel pressures at the locations of the S1 panels that failed or can produce only marginally higher underside panel pressures before failure will occur.
- Thus the increase in pressure for S2 compared to S1 is inhibited by the limits of the panel design pressures.
- If one were to further increase the impact velocity, in more likelihood the measured underside panel pressures would not increase significantly, but that the interior structure would be more greatly affected.

- <u>Ditching compliance</u>

1. The SBIR results demonstrated that the analysis program addresses sea state conditions. Sea state is specified, but largely ignored in ditching procedures, other than in scale model testing. The hybrid analysis indicated that it could evaluate sea state, which can be a significant factor as can be observed from Figure 11, in a comprehensive manner, including taking into account wave motion and direction.

2. The SBIR effort showed that current procedures being used to determine ditching pressures and accelerations are inadequate in several regards; namely predicting sink speed related vertical load factors, dynamic pressures, longitudinal load factors, and not accounting for sea state effects. Figure 13 illustrates the hybrid modeling of the UH-1H and Osprey modeling results account for sink speed, whereas the current procedures do not. The SBIR demonstrated that analytical modeling could complement current procedures and scale model testing so as to reduce cost, reduce turn-around time and evaluate conditions that are not tested.

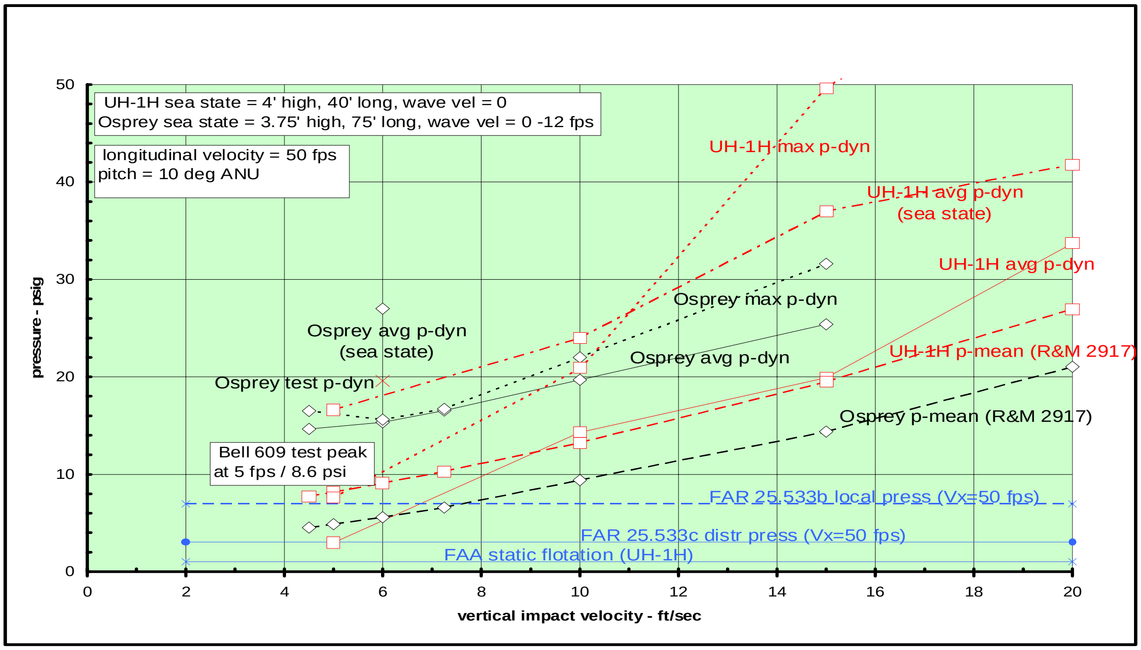


Figure 13- Comparison of Pressure for Water Impact Landings-DRI/KRASH VS. Static Load Calculations

- <u>Design related studies</u>

1. The UH-1H parameter studies showed that there is virtually no limit to the range of the sensitivity studies that can be performed. The separation of the seat and occupant masses from the floor slab mass illustrates how the floor pulse is affected. The floor response associated with the lighter weight is much higher (70 g) than a corresponding heavier slab response (37 g).
2. Also the separation of floor, seat and occupant masses allows for a determination of the effect of load limiting energy absorbers on occupant loads and seat stroke. While these parameters are best investigated with seat-occupant models like SOMLA and Madymo, the SBIR demonstrated that this effect could also be approximated with the hybrid model. Figure 14 shows that the analysis displays the proper response sequence for the floor, the seat and

the occupant. It also shows how the occupant spinal load (dynamic response index (DRI) or lumbar load) is reduced, depending on limit load, while not affecting the floor pulse.

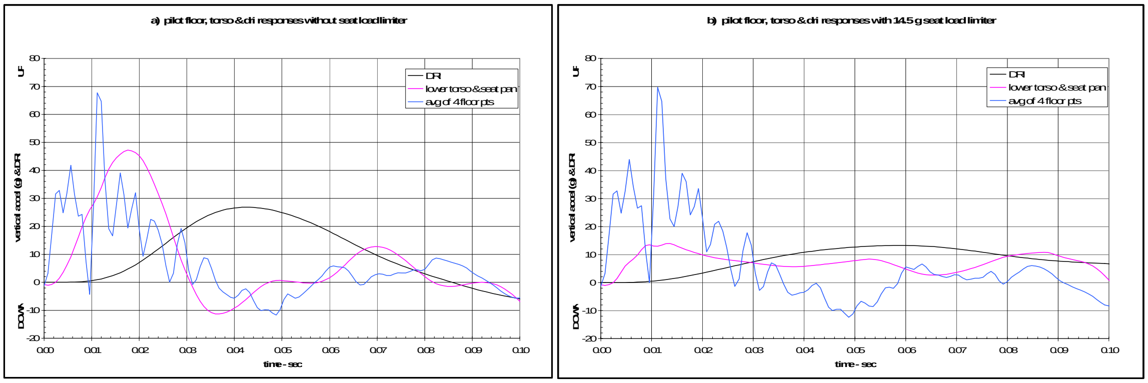


Figure 14 – Effect of 14.5 g Load Limit Seat

3. The analysis demonstrates the ability to evaluate the effect of energy management features, such as an energy absorbing landing gear. Figure 15 shows that the dissipation of the kinetic energy over time and the floor pulse are effected. For the oleo design used, It was shown that the energy absorbing oleo could reduce the lumbar load 31 %, the seat stroke 5 % and the average floor peak acceleration 42 %.

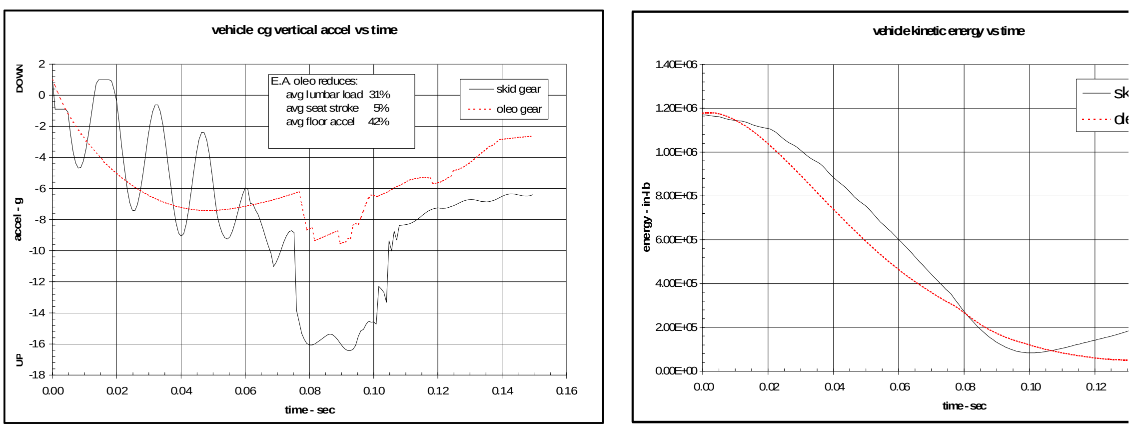


Figure 15 – Energy Absorbing Oleo Versus Skid Type landing Gear

- <u>Design Limit Envelopes</u>

1. A Preliminary DLE is presented to illustrate the current approach which takes into account; underside panel failure, occupant floor failure, lumbar load, seat load and stroke limits, interior design pressures, mass item retention. The DLE shown is for a specific design and impact. A series of DLE are being developed and floor pulses obtained to compare with current seat dynamic test requirements. The particular illustration, provided in Figure 16, denotes where criteria is exceeded for civil rotorcraft 95th percentile accident limits. It is based on a specific FAR 27 rotorcraft.

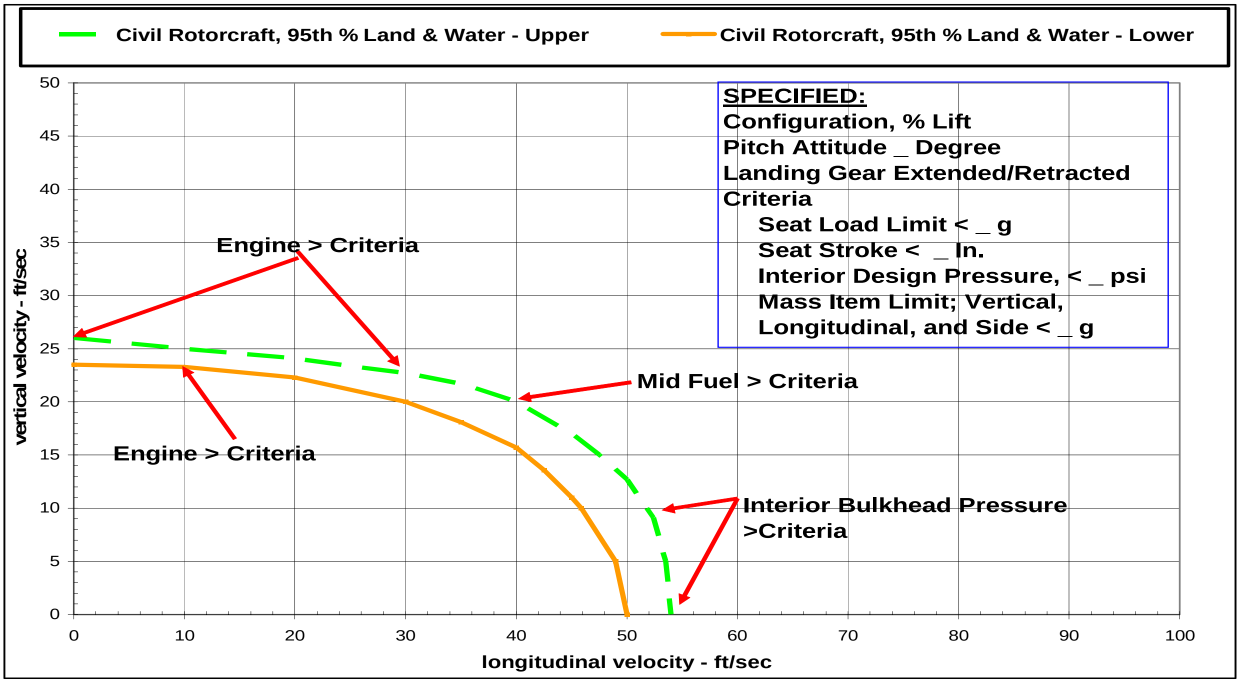


Figure 16 Sample Severe Water impact DLE

Figure 17 illustrates a ditching DLE for a military rotary wing configuration and how an operational condition, such as One Engine Inoperative (OEI) can be evaluated with respect to a DLE. Of interest is how the current ditching criteria (Table 4) compares with the DLE obtained via the KRASH studies.

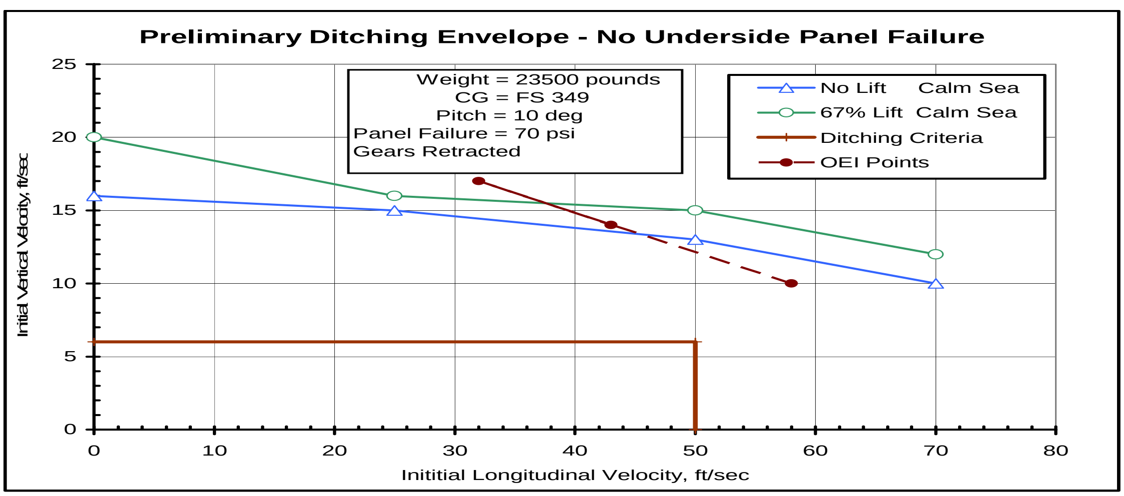


Figure 17 Potential Ditching DLE Application

Table 4 Ditching Design Conditions

Parameter	Navy	Civil
Sea State (wave height - ft)	2 2	4 4 to 8
Weight Landing Gear	Structural design Extended and alternately retracted	Not stated Not stated
Sink Speed - ft/sec Forward Speeds - kts Attitude	6 0 to 30 All possible flare angles	5 30 Optimum pitch, 15 deg yaw

The process of DLE development is being expanded with the incorporation of head injury criteria, illustrated in Figure 18, for different floor pulses, different head strike surfaces, and including current seat dynamic test requirements.

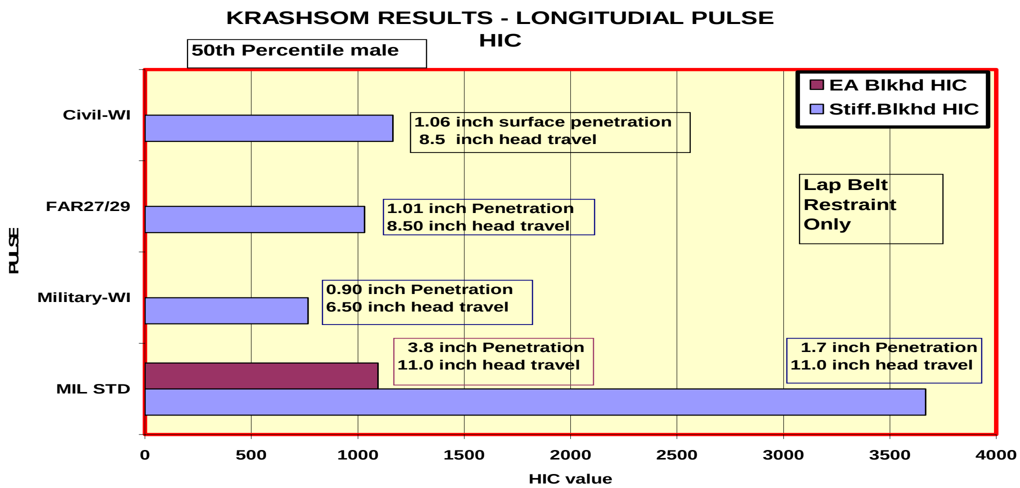


Figure 18 HIC Vs. Seat dynamic Test Requirement and Head Impact Surface

CONCLUDING REMARKS

1. The development of Ditching design criteria and DLE curves requires a significant number of simulations and rapid turn-around time. Analytical modeling with the hybrid program provides versatility, flexibility and fast response time. The FEM provides alternative benefits for detail design considerations. As noted in Table 5, the hybrid approach is significantly faster and more convenient for full aircraft simulation of multiple cases than the FEM approach.

2. The SBIR results demonstrated that survivable crash and ditching envelopes based on previous military and civil accident data may not be representative of current designs. Design limit envelopes may be possible with analysis as an alternative to costly scale model ditching tests, relying on accident data profiles, or using existing seat dynamic test requirements from ground impact criteria.

Table 5 FEM-HYBRID Time Tradeoff

PARAMETER	S1 pretest correlation		S2 pretest correlation	
	FEM	**HYBRID**	**FEM**	**HYBRID**
Run time comparisons				
maximum simulation time	0.035 sec	0.100 sec	0.050 sec	0.300 sec
computer run time	12 hours	2 min	14 hours	6 min
operational system	IBM RISC 6000 / Silicon R8000	333 MHz Pentium II PC	IBM RISC 6000 / Silicon R8000	333 MHz Pentium II PC

3. Additional refinements are being made to the preliminary design limit data shown in Figures 16 and 17 taking into account the many factors that have to be considered. This ongoing effort for both the NAWCAD and FAA may show design curves that are different in some regards to those shown, and will be discussed in future presentations.

4. A family of DLE curves is currently under development for the FAA for FAR27/29 civil rotary-wing aircraft and involves several airframe designs, impact conditions, and criteria. The range of these variables is noted Table 6. The objective of the effort is to provide potential ditching and water impact design criteria.

5. The DLE development technology and procedures are also applicable to FAR 25 aircraft because the FAR25, 27 and 29 ditching requirements, seat dynamic test requirements, and compliance techniques are similar, albeit at different levels.

Table 6 Range of Considerations for FAR27/29 Design Limit Envelope Development

CONSIDERATIONS		DITCHING	WATER IMPACT
Configurations Modeled		GTOW Max Design Landing Amphibious/Float Auxiliary Fuel Tank	GTOW Max Design Landing Amphibious/Float Auxiliary Fuel Tank S1, S2 Test Article
Design Envelope		FAR27/FAR29	Civil 95th Percentile -Upr Civil 95th Percentile-Lwr
Vertical Velocity	Ft/Sec.	0 to 25	10 to 28
Longitudinal Velocity	Ft/Sec.	0 to 75	0 to 60
Pitch Attitude	Degree	0, 5, 10	0, 4, 5, 10
Roll, Yaw	Degree	10	10
Sea State		Calm Sea State 4	Calm No
Rigid seat		Yes	No
Load Limit Seat	g	12, 14.5	12, 14.5
Criteria			
Seat Stroke limit	In.	5	5
Lumbar Load Limit	Lb.	1500	1500
Underside Panel Failure	psi	Design	Design
Interior Bulkhead Failure	psi	No	20
Head Injury	HIC	1000	1000
Restraint Belt Load	Lb.	1750-2000	1750-2000
Mass Item Restraint Engine Transmission Fuel	g	30/30/15 <1>	30/30/15 <1>
<1> Vertical/Longitudinal/ Side			

ACKNOWLEDGEMENTS

The civil helicopter related effort is performed under the sponsorship of the Federal Aviation Administration-Technical center (FAA-TC). Steve Soltis, Gary Frings and Tim Smith have provided valuable guidance and direction.

The military helicopter related effort is performed under the sponsorship of the Naval Air Warfare Center - Aircraft Division (NAWCAD) with Mike Schultz as the principle technical advisor.

Valuable contributions with regard to test, analysis, and data have come from Bell Helicopter-Textron (BHTI), Simula Technologies (STI), and the U.S. Army Prooving Grounds – Yuma, Arizona.