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THE ROLE of FLIGHT TESTING and ENHANCED FINITE ELEMENT ANALYSIS for ROTORCRAFT SERVICE LIFE EXTENSION PROGRAMS

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ABSTRACT

The USAF has established a requirement to use the HH-60G as its primary Combat Search and Rescue helicopter for an airframe operating life of 20,000 flight hours with extended use through 2015. The Australian Defense Forces (ADF) uses it H-60 variant in the utility helicopter role with a planned withdrawal from service date of 2015. The Army's original specification for the H-60 aircraft contains no specific airframe life, but required an airframe designed to avoid major overhaul in less than 8,000 flight hours. No analysis or laboratory test to define an airframe life have been conducted for any of the Army, USAF, or ADF H-60 variants.

A review of the records of many HH-60Gs (USAF) and UH-60A/Ls (Army) inventory has identified over 100 airframe structural distress areas that may need fatigue strength enhancements. The necessary technical data needed to preclude the reoccurrence of airframe cracks required an extensive flight strain survey of a heavily instrumented helicopter, which is one subject of this paper.

The Support Command Australia and the USAF's Warner Robins Air Logistic Center (WR-ALC) were the sponsors of these tests. The Georgia Tech Research Institute (GTRI) served as the prime contractor with the Sikorsky Aircraft Corporation (SAC) as its principal subcontractor and significant technical contribution from Advanced Structural Technologies Inc. (ASTI). Flight activities were conducted by the ADF's Aircraft Research and Development Unit (ARDU) located at the RAAF Edinburgh Base (near Adelaide) Australia. Two external configurations were tested for a total of 65 productive flight test hours.

The maneuvers performed included those in the mission usage spectrum of both the ADF or USAF H-60's. Approximately 39 generic survey maneuvers were performed at each loading except at altitude were IGE flight was not possible. This process resulted in slightly over one million data points. Gages located near known "hot spots" recorded high stress levels which demonstrates the reason for the distress (cracks).

This flight strain data offers the opportunity to enhance the capability of current analytical load predictions. These predictions will be improved by using a regression (least-squares) procedure. The test data for the various regimes in the usage spectrum are initially compared to the raw predictions made using external load predictions and load distribution codes (GenHel/FEM) in order to subsequently establish a matrix of correction factors for each specific regime.

Detailed fatigue analyses of the critical locations and modifications to these locations using the Local Strain Life Method will be performed, together with automated generation of the stress spectra at designated critical locations. The stress spectra is generated by stepping through the time points in the finite element simulation of a maneuver to identify, for each critical location, the valley and peak for the quasi-steady stresses. This method results in a unique stress history for each critical site. The vibratory stress for each location is superimposed on the mean stress history obtained by this time-stepping to form the cyclic stress history for the maneuver. The stress histories are then combined, based on anticipated usage, into the stress spectra for each location or sub-zone.

The advantage -- it utilizes the loads-correlated FEM of the airframe to generate stress histories at non-gaged locations, while ensuring that the response at gaged locations matches the recorded flight test stress histories in a least-squares sense.

INTRODUCTION

The USAF has established a requirement to use the HH-60G as its primary Combat Search and Rescue helicopter for an airframe operating life of 20,000 flt hrs with extended use through 2015. The ADF uses its H-60 variant in the utility helicopter role with a planned withdrawal from service data of 2015. The Army's original specification (for the H-60) does not contains an airframe life requirement, but specified that the airframe be designed so as not to require overhaul in less than 8,000 flt hrs. No analytical studies or laboratory test to define an airframe life have been conducted for any of the Army, USAF, or ADF H-60 variants. The USAF's current position is that no new missions are envisioned for this aircraft, however its mission and on-board mission equipment with frequent upgrades constitutes a unique H-60 variant.

Administratively, arrangements for a joint USAF/ADF flight test program were accomplished through the use of *Project Arrangement S/N AF-00-0023 Between the Government of the United States of America and the Government of Australia Concerning Cooperative and Collaborative Research, Development and Engineering for a S-70A-9 / HH-60G Flight Loads and Strain Survey, dated 13 July 2000.*

FIELD SERVICE RECORDS

The first step in the planning process was to identify H-60 airframe fatigue problems by reviewing data from three separate sources. These included the Joint Airframe Condition Evaluation (JACE) reports, Sikorsky field service records, and aircraft maintenance personnel at the Corpus Christi Army Depot (CCAD). The JACE reports contained both Army and USAF aircraft evaluation results. Over 5100 discrepancy reports from 1997 and 1998 JACE evaluation data revealed over 2600 fatigue problems occurring over 650 Army and 60 USAF H-60's. These evaluations covered approximately 48% of the Army fleet and 60% of the USAF fleet. In depth analysis resulted in 114 separate "hot spots" to be addressed during SLEP. A summary of aircraft included in the JACE inspections is presented in the following Table.

TABLE 1-SUMMARY OF A/C/ JACE INSPECTIONS

Aircraft Flt Hrs in 1000s	USAF				US Army			
	1997		1998*		1997		1998*	
	No in Fleet	No of JACE	No in Fleet	No of JACE	No in Fleet	No of JACE	No in Fleet	No of JACE
8-9K	-	-	-	-	1	1	4	1
7-8K	-	-	-	-	12	11	11	7
6-7K	-	-	1	-	15	13	15	8
5-6K	4	3	7	2	9	6	7	3
4-5K	5	4	1	2	7	5	7	3
3-4K	5	0	9	2	55	29	81	42
>3K	(14)	(7)	(18)	(6)	(99)	(65)	(125)	(64)
2.5-3K	7	1	9	2	227	126	249	111
2-2.5	12	7	20	9	341	169	357	163
<2K	67	46	50	39	754	326	704	315
Totals	100	61	97	56	1421	686	1435	653

* Data for inspections performed through Sept 1998

It was important to prioritize the above mentioned distressed areas into criticality categories to establish the relative importance of implementing repairs and/or fatigue strength enhancements as shown below.

- **CATEGORY A**: Critical/major problems having direct impact on the airframe structural integrity and safety of flight.
- **CATEGORY B**: Not directly affecting safety of flight, but having some impact on airframe structural integrity.
- **CATEGORY C**: Problems not directly affecting airframe structural integrity, but representing significant maintenance costs.

The distribution of these distressed areas is better illustrated by using an airframe structural description isometric drawing. The following three figures illustrate that of the total of 114 airframe fatigue problems identified (total of 2588).

33 are Category A (676 collective occurrences),
45 are Category B (899 collective occurrences),
36 are Category C (1013 collective occurrences).

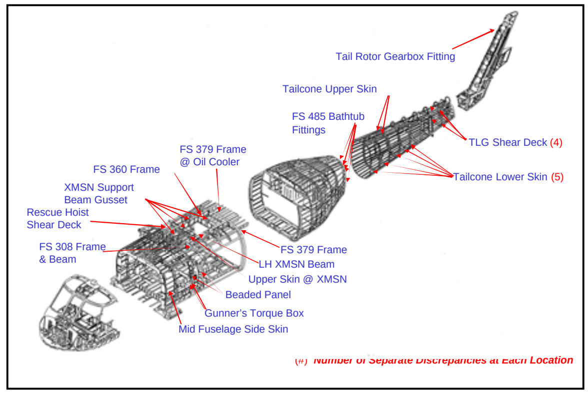

Figure 1 - Category A, Major, Impacts on Structural Integrity.

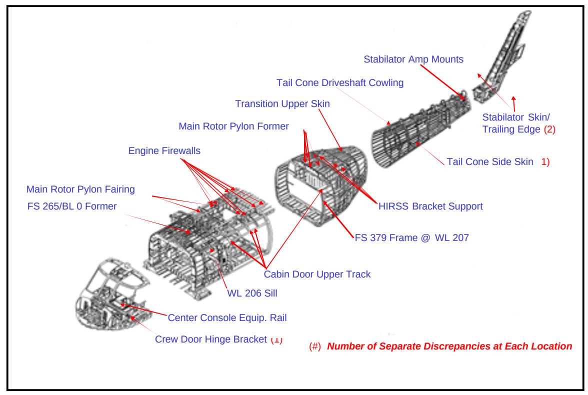

Figure 2 - Category B, Sub-Critical Structural Discrepancies.

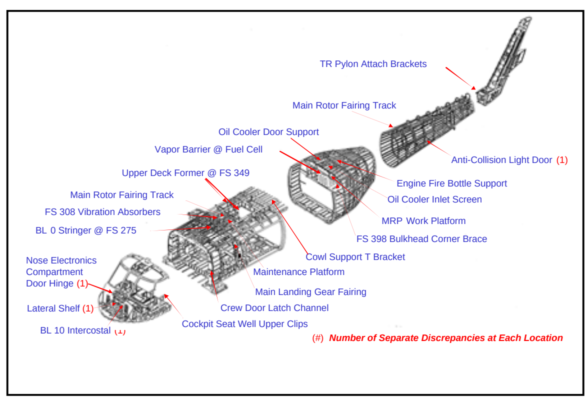

Figure 3 - Category C, Minor Structural Integrity, but Maintenance Burden.

TEST INSTRUMENTATION

The massive instrumentation required for the airframe flight strain survey consisted of 4 types of parameters which included flight state and control system parameters, dynamic component strain gages, airframe strain gages, and airframe mounted accelerometers. Tables 2 thru 4 list the measured parameters.

TABLE 2 - FLIGHT STATE & CONTROL SYSTEM PARAMETERS

Boom Airspeed	*Roll Rate*
Boom Altitude	*Yaw Rate*
Boom Rate of Climb	*Pitch Acceleration*
Angle of Attack Vane	*Roll Acceleration*
Sideslip Vane	*Yaw Acceleration*
Boom Outside Air Temp	*Normal Load Factor @ CG*
No. 1 Engine Torque	*Collective Position*
No. 2 Engine Torque	*Directional Pedal Position*
No. 1 Eng T4.5 (TGT)	*Longitudinal Position*
No. 2 Eng T4.5 (TGT)	*Lateral Cyclic Position*
Pitch Attitude	*Stabilator Position*
Roll Attitude	*Main Rotor Speed*
Heading	*Main Rotor Contractor*
Pitch Rate	*Tail Rotor Contractor*

TABLE 3 - DYNAMIC COMPONENT GAGES

PARAMETER	*No. Gages*	*No. Channels*
MR Blade Normal Bending	*4*	*1*
MR Blade Edgewise Bending	*2*	*1*
MR Pushrod Load	*2*	*1*
MR Fwd Long Stationary Servo	*4*	*1*
MR Lateral Stationary Servo	*4*	*1*
MR Aft Long Stationary Servo	*4*	*1*
MR Stationary Scissors	*4*	*1*
MR Shaft Extender Torque	*16*	*4*
MR Shaft Extender Bending	*8*	*2*
MR Control Bridge Right Tie Rod	*4*	*1*
MR Flapping Angle	*Derived*	*0*
TR Stationary Control Load	*4*	*1*
TR Blade Spar Flatwise Bending	*2*	*1*
TR Torque	*12*	*3*
TR Hub Bending Moment	*2*	*1*
TOTAL	*72*	*20*

The dynamic component gage measurements shown covers all the substantiating parameters for component retirement times (CRT) calculations, however, resubstantiation of CRT's for dynamic components was not a part of this program. Through tri-service agreements the US Army is responsible for all product improvement of H-60 dynamic components, therefore, this SLEP effort relates only to the airframe, tail pylon and stabilator. In addition, the full range of gross weight/center of gravity/density altitudes were not covered by these tests. Emphases was placed on low density altitude conditions were the airframe felt the highest dynamic pressure.

All parameters listed were recorded through a MicroDAS-1000 Data Acquisition System. The test aircraft did not incorporate a multi-plex database as a normal source for many parameters.

TABLE 4 - AIRFRAME STRAIN GAGES & ACCELEROMETERS

Section	Locations Description	Strain Gages Installed	Strain Gage Channels	Accelerometer Channels
Cabin	Beaded Panel	8*	24	
	FS 308 Center Line	1	1	-
	FS 308 Door Frame	12	12	-
	BL 16.5 Longitudinal Xmsn Beam	32	32	-
	BL 34.5 Longitudinal Xmsn Beam	8	8	-
	FS 327 Lateral Xmsn Beam	8	8	-
	FS 343.5 Frame	20	20	-
	FS 360 Lateral Xmsn Beam	10	10	-
	BL 0 at FS 360 Intercostal	3	3	-
	FS 379 Frame	12	12	-
	BL 0 at FS 379 Intercostal	1	1	-
Tailcone	FS 485 Longerons	4	4	-
	Sidewall Skins	3*	9	-
Tail Pylon	LH and RH Skins	24	24	2 (2 Ny)
	Flatwise Bending Bridges	16	4	
	Shear Bridges	16	4	
Horz Stab	Center Box Rosette	3	3	1 (Nz)
	Bending Bridges @ BL 9, 13, 16, 29, 57	40	10	4 (4 Nz)
ESSS	Support Struts	4	4	-
MR Pylon	Engine Cowling	8	8	4 (Ny, Nz)
	APU Door	4	4	1 (Nz)
	HIRSS	12	12	4 (2 Ny, 2 Nz)
	Oil Cooler Support			2 (Ny, Nz)
	* 3 Gage Rosettes on Single Backing **Total**	**249**	**217**	**18**

Fatigue assessments were performed to identify locations which have been crack free, but with a high probability of cracking prior to 20,000 hrs and locations susceptible to dynamic magnification of vibratory stresses. The relationship between strain gage locations and distress areas can best be viewed using the following gage location illustrations.

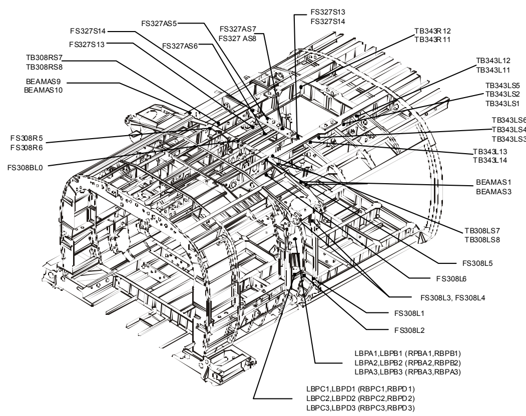

Figure 4 - Forward Cabin Gage Locations

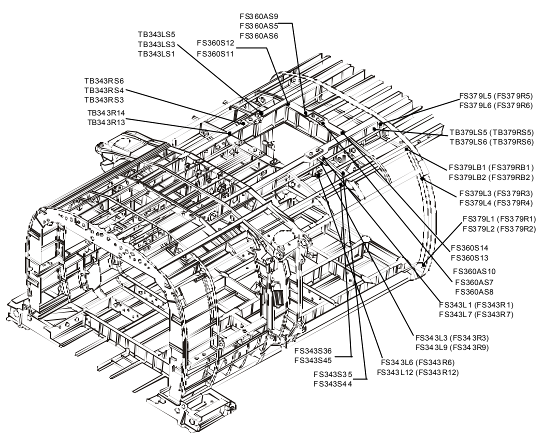

Figure 5 - Aft Cabin Gage Locations

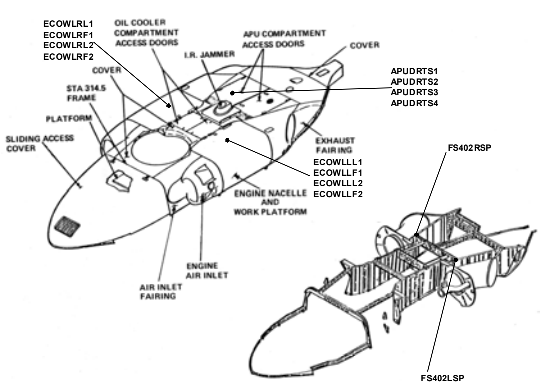

Figure 6 - Main Rotor Pylon Gage Locations

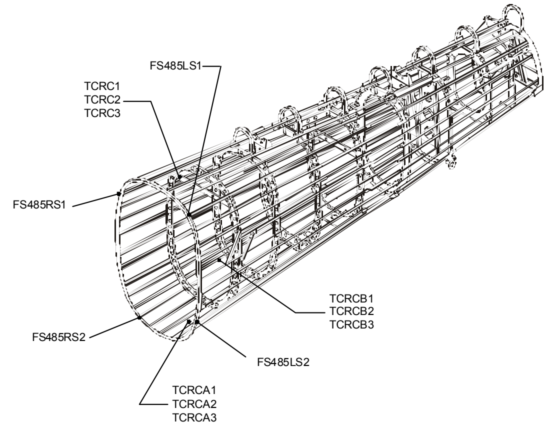

Figure 7 - Tail Cone Gage Locations

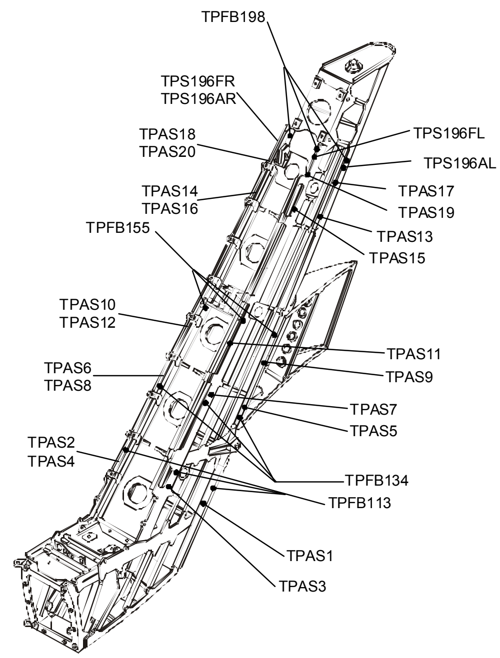

Figure 8 - Tail Pylon Gage Locations

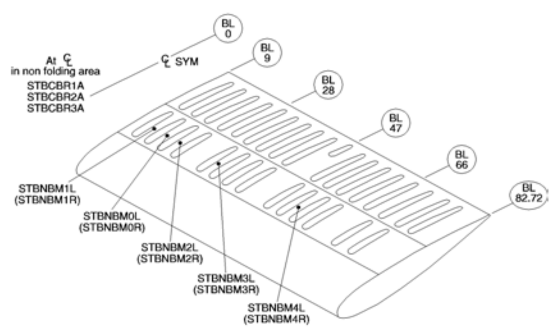

Figure 9 - Stabilator Gage Locations

Note that both the HH-60G & S-70A-9 incorporate rectangular stabilizer with folding capability (not shown) rather than the US Army tapered chord stabilator.

SCOPE OF TEST

A total of 16 gross weight / center of gravity loadings were flown. Seven were with a clean configuration, 6 with the external stores support system (ESSS) incorporating a 230 gal fuel tank on the outboard station and the 7th incorporated four 230 gal fuel tanks to simulate the ferry mission loading. One of the clean configuration loadings included an external rescue hoist with a 600 lbs load and another at 8000 lbs external cargo sling load. Three aircraft loadings were repeated at 8,000 ft density altitude (Hd). All other flights were targeted for 3,000 ft Hd except for in-ground effect (IGE) work, which normally ran approximately 1500 ft Hd. The two figures below illustrate the target loadings and the start and end point of that data collection illustrating the impact of fuel burn on both GW and CG.

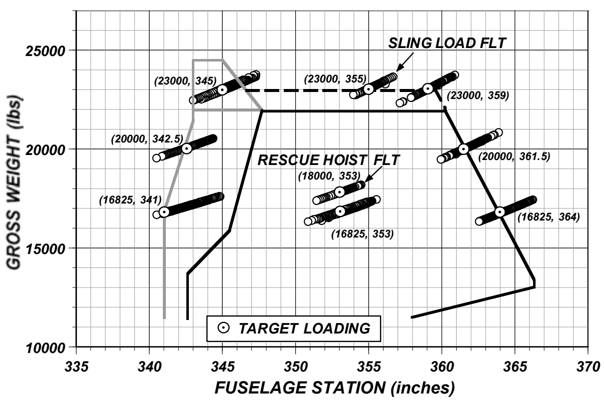

Figure 10 - Clean Configuration Loadings

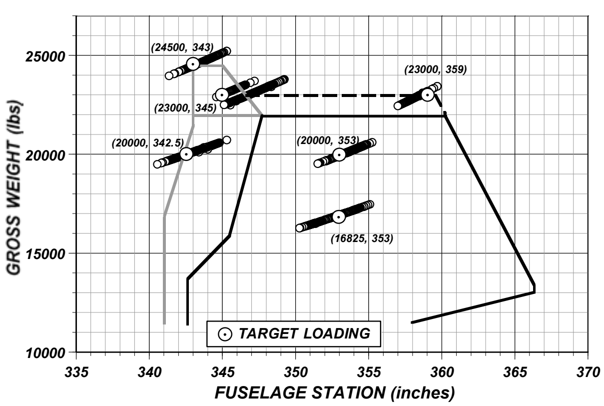

Figure 11 - ESSS Configuration Loadings

The maneuvers performed during this test included in the mission usage spectrum of both the ADF's S-70A-9 or the USAF's HH-60G for purposes of determining component retirement times. Rolling pullouts, which are normally considered a structural demonstration maneuver were also performed because of the maneuver's unique loading of the airframe. The pullout components results in fuselage vertical bending and the rolling components result in fuselage torsional bending. Their combination is highly variable depending upon the phasing of the longitudinal and lateral cyclic inputs. As will be explained later, rolling pullouts present the most interesting test results. A generic list of maneuvers planned for each CG loading is presented in the following table.

TABLE 5 - GENERIC FLT STRAIN SURVEY MANEUVERS

- ✔ ***Rotor Engagement to 100% Nr, Shutdown***
- ✔ ***Ground Taxi Including Taxi Turns***
- ✔ ***Hover IGE and OGE***
- ✔ ***Lt & Rt Hover Turn (15° ft/sec & 30° ft/sec)***
- ✔ ***Lt & Rt Sideward Flt (Hover to 45 kts, 5kt Intervals)***
- ✔ ***Air Taxi & Rearward Flt (Hover to 45 kts, 5 kt Intervals)***
- ✔ ***Dash/Quick Stop, Side Flt from Hover***
- ✔ ***Dash/Quick Stop, Fwd Flt from Hover***
- ✔ ***Hovering Reversals - Long, Lat, Pedal & Coll***
- ✔ ***Takeoff and Climb;*** V_{broc}***, 106% Q***
- ✔ ***Level Flt -*** $.4V_h$, $.5V_h$, $.6V_h$, $.7V_h$, $.8V_h$, $.9V_h$, V_h
- ✔ ***Dives -*** $1.1V_h$ ***&*** $1.2V_h$ ***KIAS @ 100% Nr***
- ✔ ***Lt & Rt Sideslips;*** $.8V_h$ ***&*** V_h
- ✔ ***Level Flt - Long, Lat, Pedal & Coll Reversals;*** $.8V_h$ ***&*** V_h
- ✔ ***Level Flt -*** $.6V_h$ ***&*** $.9V_h$ ***@ 95%, 97%, 99%, & 101%***
- ✔ ***Lt & Rt Rolling Pull-outs;*** $.8V_h$ ***&*** V_h
- ✔ ***Mod & Severe Symmetrical Pull-ups;*** $.8V_h$ ***&*** V_h
- ✔ ***Pushovers;*** $.8V_h$ ***&*** V_h
- ✔ ***Terrain Cyclic Pull-up; 40 KIAS***
- ✔ ***Terrain Cyclic Push-over; 40 KIAS***
- ✔ ***Climbs;*** V_{broc}***, &*** V_{broc} ***± 15 Kts***
- ✔ ***Climbing and Descending Turns;*** V_{broc}
- ✔ ***Lt & Rt Turns (to 60° AoB);*** $.8V_h$ ***&*** V_h
- ✔ ***Entry & Recovery for above Turns***
- ✔ ***Lt & Rt Rapid Decelerating Turns***
- ✔ ***Vertical Takeoff***
- ✔ ***Collective Pop Up (Jump Takeoff)***
- ✔ ***Part Power Descent (1500 fpm) 90 KIAS***
- ✔ ***Recovery from Partial Power Descent***
- ✔ ***Entry Autorotation from*** $.8V_{ma}$ ***&*** V_{ma}
- ✔ ***Autorotation @ 110% Nr;*** $.8V_{ma}$ ***&*** V_{ma}
- ✔ ***Auto Long, Lat, Pedal & Coll Revs;*** $.8V_h$ ***&*** V_{ma}
- ✔ ***Lt & Rt Autorotation Turns;*** $.8V_h$ ***&*** V_{ma}
- ✔ ***Power Recovery from Autorotation;*** $.8V_h$ ***&*** V_{ma}
- ✔ ***Approach to Hover (Normal, Rough, Oper)***
- ✔ ***Running Takeoff***
- ✔ ***Vertical Landing***
- ✔ ***Simulated Shipboard Landing***
- ✔ ***Run-on Landing***

The practical maneuvers that could be performed with an external sling load or less than those shown above. The space limit of this paper does not permit their listing herein.

For the maneuvers flown, their relationship with the flight envelope limits will be presented for sample loadings. The limitations for normal load factor warrant some discussions. The test aircraft had a normal accelerometer display (g-meter) on the instrument panel, although not provided on standard operational aircraft. This instrument was used to control the severity of turns, symmetrical pull-ups and pushovers, and rolling pullouts to avoid severe blade stall. An empirical value of Equivalent Retreating Blade Indicated Tip Speed (ERITS) in knots is used to define the onset of blade stall, moderate stall, full stall and sever blade stall. The equation below defines ERITS in mathematical terms normalized to some desired design conditions.

$$ERITS = \left(V_R \sqrt{\frac{\rho}{\rho_O}} - V_I \right) \sqrt{\frac{W_O}{W} \frac{A_O}{A}}$$

Where:

V_R	Blade Rotational Tip Speed (kts)
V_I	Indicated Airspeed (kts)
ρ_O	SL Standard Air Density (slugs/ft^3)
ρ	Actual Air Density (slugs/ft^3)
W_O	Normalizing GW = 16,500 lbs
W	Actual GW
A_O	Normalizing Load Factor = 1g
A	Actual Load Factor

For the H-60, with its advance airfoil geometry and swept tip, an additional adjustment is needed to account for the variation in maximum lift coefficient with Mach number. This is known as a Mach corrected ERITS and is determined by a parametric method which is proprietary to Sikorsky. When applied, the Mach corrected ERITS values were 220 kts for the onset of blade stall and 180 kts for full stall.

It can be seen from the test target envelopes on some of the following charts that the target load factor was limited to a Mach corrected ERITS of 180 kts at speeds above Vcr. It is important to understand that the flight strain survey test conditions in no way portray the full aerodynamic flight envelope of the H-60.

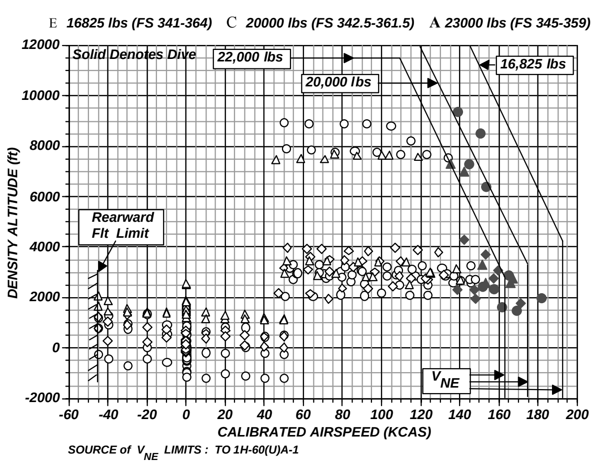

Figure 11 - Density Altitude vs Airspeed, Clean Config

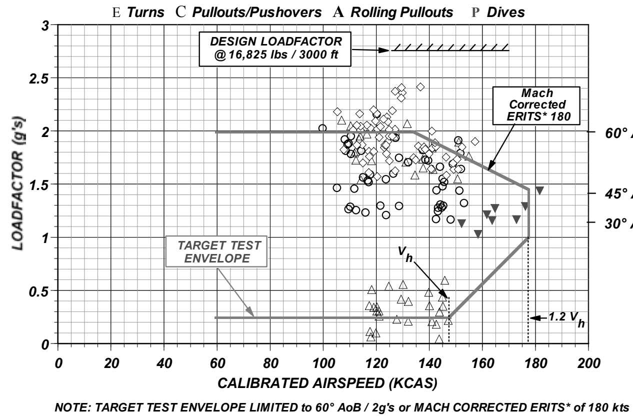

Figure 12 - Loadfactor vs Airspeed, Clean Config
GW= 16,825 lbs, 3,000 ft Hd

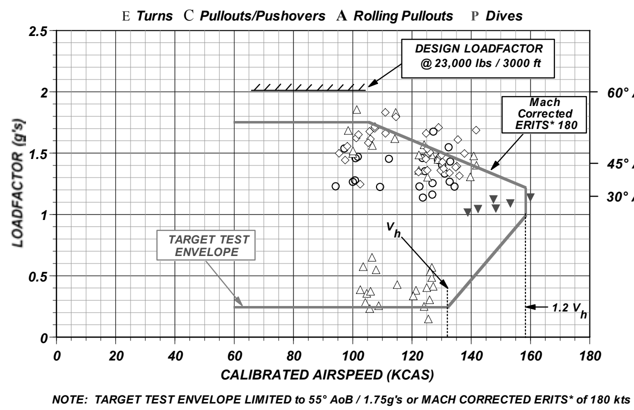

Figure 13 - Load factor vs Airspeed, Clean Config
GW 23,000 lbs, 3,000 ft Hd

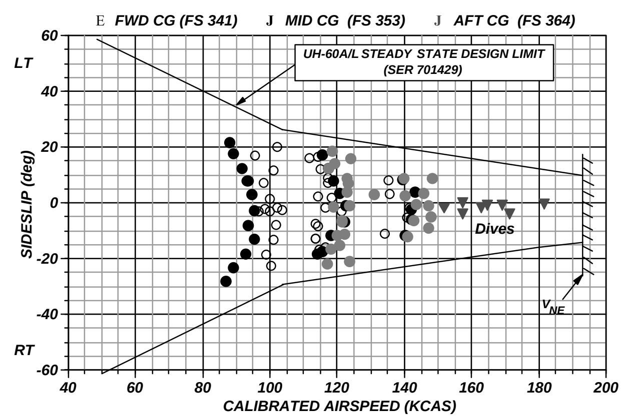

Figure 14 - Sideslip vs Airspeed, Clean Config
GW 16,825 lbs, 3,000 & 8,000 ft Hd

The above figures are samples of data that was obtained for all of the airframe strain gages and accelerometers and the dynamic component strain gage measurements as well. The entire test program resulted in 1,065,212 discreet data points.

BRIEF DISCUSSIONS of RESULTS

The absolute value of the loads, as recorded, can be separated into a steady component and a vibratory component. For the purposes of subsequent modification of computer models of the helicopter loads' behavior using SAC's GenHel model, the maximum steady statistic is considered highly relevant. A review of the data to determine which maneuvers generated the 5 highest maximum steady loads in the airframe gages was performed with the results shown below. A simplified list of eleven maneuvers, or appropriate combinations thereof, was consolidated from the complete listing covering all loading configurations.

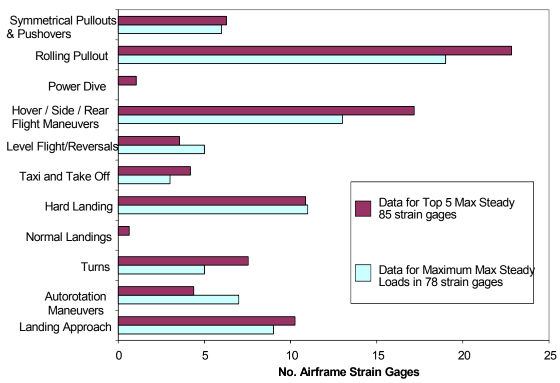

Figure 15 - Maneuvers Generating Highest Maximum Steady Loads for "High Reader" Airframe Strain Gages

Based on the data shown in Figure 15, the Rolling Pullout maneuver affects the highest number of gages, whose locations range over all areas of the airframe.

The Landing Approaches mainly affect the gages around the area at the forward end of the main transmission beams in the cabin while the Hard Landings affect the areas at the sides and the FS 308 frame where the undercarriage is mounted. Autorotation affects only the tail pylon and the ESSS struts. Low speed flight and hover affect the upper end of the tail pylon and the HIRSS supports.

FLIGHT TEST DATA EVALUATION (Loads and Strains)

Review of the aircraft GW and CG loadings and the corresponding flight data recorded was needed initially to assure that stress spectra for the design of fatigue enhancements/ modifications could be generated. Determination of the impact "corner-of-the-envelope" GWs and CGs flown on the S-70A-9 on the HH-60G stress spectra was the next step performed. Completion of the bulk of the strain gage and accelerometer data for subsequent flights for anomalies, initiated in an earlier phase of the program, is then completed. This review consists of comparison checks to verify that each strain gage or accelerometer has recorded data within the "expected" range as previously established per the following:

- Validation that the gages and data recording system have functioned properly,
- Validation the flight test procedures,
- Establishment if any special processing, i.e., Fourier analysis, is necessary, and
- Validation of the suitability of the data for spectrum generation.

Review of the ADF's flight test data also included trending against prior available flight test data.

The maneuvers that are the most damaging for low cycle fatigue and for high cycle fatigue for each zone are identified. From these maneuvers, a short list is generated for the flight simulation and for the load correlation effort. Determination of the characteristic high frequency factors relating the vibratory stresses to the steady stresses for each structural zone is performed. Zone boundaries will then be determined based on the limits to which a set of high frequency factors can be reasonably assumed to be applicable. These high frequency factors will be used to generate a vibratory response map of the airframe to allow the vibratory stresses to be determined for each of the locations for which fatigue analyses will be performed. For locations with suspected local resonant modes, Fourier analyses to identify the mode and resonant frequency will be performed.

Extraction of external applied tail rotor thrust and torque, stabilator and vertical pylon lift from empennage bending bridge steady measurements must then be accomplished. These results are provided for correlation with the flight simulation model.

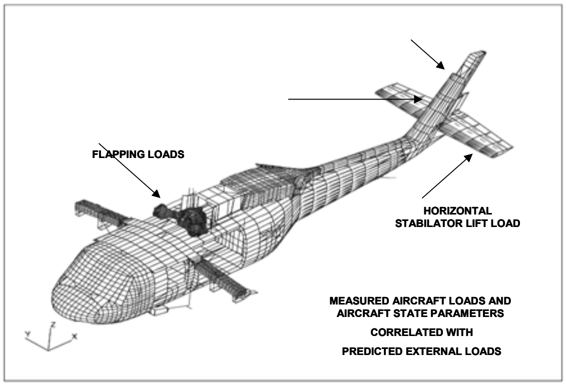

Figure 16 – Loads and Aircraft State Parameters to be Correlated with Flight Test Data

SIMULATION & FINITE ELEMENT MODEL UPDATE and VALIDATION

In order to properly understand the causes behind fatigue structural issues, the internal loads of the airframe must be able to be modeled. The effort associated with the finite element model update deals with representing the actual aircraft used for flight testing which is the S-70A-9 variant. This entails determining the level of detail required to account for mass distribution associated with mission equipment/ avionics, flight test peculiar equipment and any structural modifications which may exist on the test article. Since dynamic response will also be evaluated, the actual structure and all mass items supported must be represented adequately. The follow-on effort of fatigue analysis requires the use of a model, which represents the USAF aircraft. The above logic applies to this variant, as well since the modifications will be determined based on this configuration.

Once updated, the models must be "validated". This effort entails an initial comparison of the test data with expected model results. Where available, prior flight test data will also be used to improve to initial fidelity of the GenHel flight simulation model and the NASTRAN FEM. Selected time histories are evaluated to determine if phase differences exist in the tabulated transient maneuver quasi-static and vibratory stresses.

Preliminary GenHel model update for ADF & USAF configurations are required as well as preliminary NASTRAN model updates.

CORRELATION EFFORT HISTORY

Prior flight testing on H-60 aircraft at SAC, circa 1987, generated significant methodology enhancements at the time. The loads correlation analysis had produced positive results which facilitate the improvement of the helicopter design process at SAC. Invaluable experience had been gained in accessing and processing raw test data. The recording of internal and applied loads parameters in addition to the usual aircraft performance data provided a database which can be addressed to answer questions on operational capabilities. In addition, the database developed during the prior programs has allowed comparison of present design methodology with the actual requirements faced by programs in their present/projected operational environment.

This earlier loads correlation analysis addressed approximately 40 parameters for each flight maneuver. This represents a data processing task of a magnitude which had not been attempted previously. As a result, the data transfer processor was improved to increase the number of parameters which could be accessed at one time. The process for converting time history data from flight test into a useful form had been improved and continues to be refined.

The methodology for obtaining direct and indirect loads data during flight testing was improved. Analysts working closely with flight test engineers allowed better data requirements to be defined. Flight test was able to derive main and tail rotor shaft bending and torque, and stabilator applied loads from direct measurements. The availability of these parameters permitted a direct comparison of the primary load generating components which create design loads.

Much work remained that could be done with these derived parameters in terms of improving basic design methodology and removing conservatism from the analysis. Additional analysis using the derived loads would be pursued in the future programs as being discussed here.

The dynamic yaw flight maneuvers performed during flight test were reproduced very well with the simulation model. For these maneuvers, the applied loads and fuselage bending loads produced by the model correlated well with the direct measurements and derived loads. The low speed pull-up maneuver also showed excellent correlation in terms of aircraft response, applied loads and fuselage bending loads. The simulation does an excellent job of reproducing loads measured during a maneuver, assuming that the maneuver dynamics are duplicated accurately.

The GenHel simulation tool has been used extensively in the generation of design loads. The addition of time history calculation of aircraft shear and bending has significantly improved this function. The time histories of shear and bending have allowed precise identification of the critical point within any maneuver. The prior correlation work had determined that the model adequately reproduced the flight path of the aircraft and corresponding loads.

Design condition limits are typically defined by specifications which often impose requirements that are outside of the feasible limits of aircraft operation. Continued development and use of simulation models to predict loads has enabled specifications accounting for such things as control input techniques, to be written in more general terms so as to enable more analytical flexibility. This represents a significant achievement in terms of realistic design loads generation and identification of critical conditions.

Lessons-learned in these prior loads correlation efforts suggested many areas which would benefit from the detailed analysis. A procedure had been established for processing raw test data which made the subsequent access to the data much faster and easier. The correlation itself would eventually benefit from further effort. Time history information from level flight conditions yielded information on the variability of the trim position and associated internal loads. Since every maneuver begins in level flight, a database could then be established for level flight also. Maneuver correlations could be improved by reviewing the initial hands-off attempts and making control corrections to create a better simulation. Maneuver controllers, which would act in response to a parameter objective, such as load factor, and produce the necessary control changes to achieve that objective, could be used to avoid control system discrepancies and directly reproduce the exact maneuver.

The use of derived loads had been explored and still deserves further consideration. The ability to derive applied loads from direct measurements represents a “closing-of-the-loop”, at the time, between engineering and flight test. The derived loads had provided a direct link between the two organizations which did not previously exist. Data could be processed more quickly since analytically generated applied loads could be compared directly without the need for interpretation, or performing the step of converting them to internal loads.

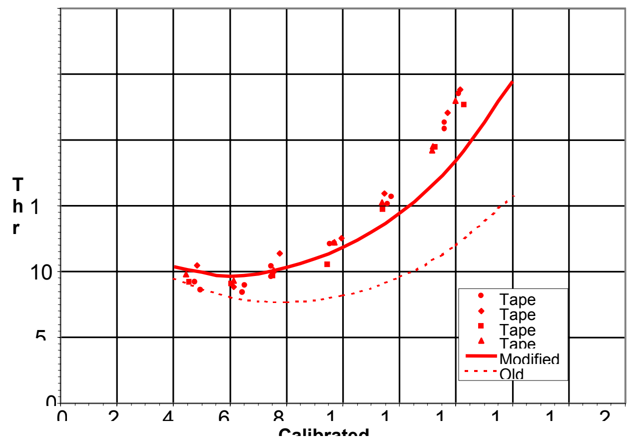

Figure 17 – GenHel Correlation Results

FLIGHT SIMULATION & FEM CORRELATION ANALYSIS

Missing from previous programs was the internal loads correlation. To truly “close-the-loop”, the methodology for predicting the helicopter internal loads must also be considered. At the time, the finite element model was not evaluated in enough detail to adequately understand the relationship between the output data which is used directly to design the aircraft with the flight test data. The program which this paper focuses on, probes into the relationship between the three legs of a complete loads correlation effort.

The flight loads, gathered as described earlier, offer the opportunity to enhance the capability of current analytical load predictions. Specifically, the current procedure makes such predictions using a global finite element model to predict quasi-static loads based on external rotor loads which are also developed analytically with the aid of GenHel (or with the corresponding ground-handling computer program for ground conditions). These predictions will be significantly improved by using a regression (least-squares) procedure whereby flight test data for the various flight regimes in the usage spectrum are initially compared to the raw predictions made using GenHel/NASTRAN in order to subsequently establish a matrix of correction factors for each specific regime. Each of these regime matrices shall be essentially a unique transfer function that shall provide varying degrees of correction to the model according to how the specific physical location in the airframe deviates in actual flight from prediction based on purely analytical means. An in-depth discussion is provided below.

The previously described correlation effort will be carried out using the updated S-70A-9 models based on the configuration used in obtaining the flight test data. The actual models used for the analysis of the USAF airframe need to be updated using the information/ expertise gained with the evaluation of the flight test representative models.

REGRESSION ANALYSIS to CORRECT the NASTRAN INTERNAL LOADS to MATCH FLIGHT TEST STRAINS

An innovative feature of the hybrid analytical/test methodology for determining fatigue lives is the regression based loads correction methodology which is used for determining "corrections" to the external loading acting on the global NASTRAN finite element model. This methodology, developed by ASTI for SAC has provided a significant step forward in automating the correlation process.

Since the effective stress concentration factor for the detail is a function of the bearing stress, the accuracy of the fatigue analysis depends upon the accuracy with which the axial and bearing loads can be predicted by the NASTRAN finite element model. In particular, the fatigue lives are sensitive to the accuracy with which the bearing loads can be predicted, since, unlike the axial stresses, the bearing loads cannot be directly measured, but must be inferred analytically. The determination of the bypass stresses and the bearing stresses, in turn, depends upon the accuracy of the external loads applied as boundary conditions to the global FEM model of the airframe.

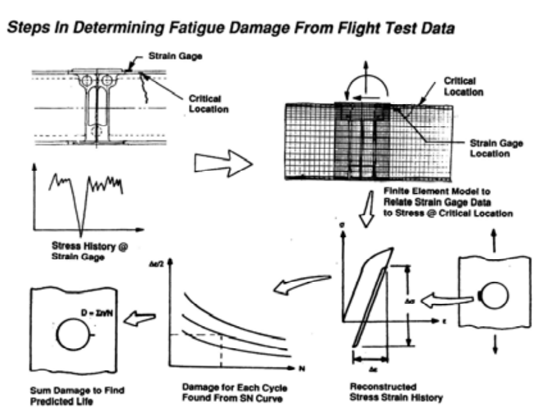

Figure 18 - Local Strain Life Method – Overview

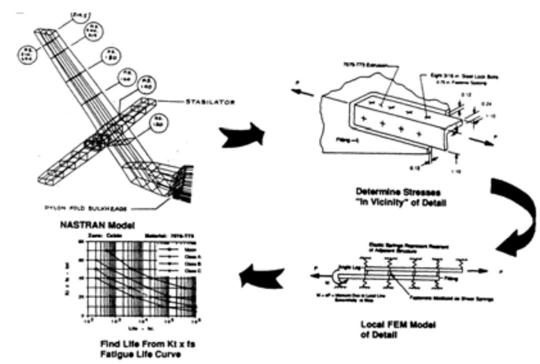

Figure 19 Global / Local Approach Determining Stresses at the Crack Site

The quasi-static component of these external loads is obtained from a GenHel analytical simulation of each maneuver. Previous experience with using GenHel for the fatigue assessment of the H-60 series helicopters has shown that significant discrepancies can exist between the analytically predicted stresses and actual measured stresses. These differences resulted from:

- Difficulties in accurately predicting the external forces applied at the main and tail rotor hubs and at the empennage, and
- Overly severe simulation of the maneuver, i.e., excessive 'g' forces.

It is key that the simulated maneuver represent, as close as possible, the test maneuver.

Accurate prediction of the loading is complicated by the effects of main rotor downwash, and the interference between the vertical tail and the rotor air flow pattern. Seemingly small variations in the predicted aerodynamic loading on the vertical pylon and horizontal stabilator can significantly affect the main rotor pitching and rolling moments due to the large moment arm between the rotor hub and the tail. These variations, in turn, lead to variations in the main transmission support beam internal loading. Even greater discrepancies have been noted between the predicted stresses and the measured stresses for the transient maneuver conditions producing the major fatigue damage, due to differences between the severity of the GenHel analytical simulation and the actual flight.

The difficulty in obtaining directly usable stress measurements and the potential for discrepancies between the theoretical and actual loadings are both recognized. Therefore, a key element of the strategy to achieve accurate fatigue life predictions is to validate the quasi-static external loads applied as boundary conditions to the FEM model using data from the flight test program. The loads are validated through a regression analysis in which the external loading acting on the FEM model is corrected to produce close agreement between the predicted and measured stresses.

In the regression analysis, the influence functions needed to determine the magnitude of the corrective components will be obtained from the FEM airframe model. The technology to perform the validation through a regression analysis is being developed as part of an effort to extend the life of other H-60 variants, and the required software is available for the USAF flight test program. This software will permit both experimentally and analytically determined influence functions to be used separately, or in combination.

The figure below schematically illustrates how the external loads will be corrected using regression analysis. Strain gages will be strategically located to permit both the external loads to be verified, and to obtain point stress information at critical locations. Typical locations include the upper deck in the vicinity of the transmission support beams and frames, and in the tail rotor pylon. The strain gages used for extraction of external loads will permit stresses to be measured at key locations. These stresses can be compared against the stresses predicted by the NASTRAN model to determine the degree of error.

Corrections to the external loadings will be determined, by generating from the FEM, influence coefficients which relate each of the unknown applied external forces to the stresses at each of the strain gage locations. Applied loads which can be perturbed to determine the response sensitivity at each location include:

- Main rotor lift, side and forward force
- Main rotor head moment and azimuth angle
- Tail rotor thrust, lift and drag force
- Tail rotor head moment and azimuth angle
- Translational accelerations at the centroid
- Rotational accelerations at the centroid
- Aerodynamic forces

The ability to treat the centroidal accelerations as "correctable" degrees-of-freedom is important, as it allows adjusting the analytic simulation to the way the aircraft is actually flown. By perturbing the values of each of the applied load components and accelerations, the sensitivity coefficient relating the change in the applied load component to the change in stress at a location can be determined. The analytically derived sensitivity coefficients can be used, together with any experimentally determined influence

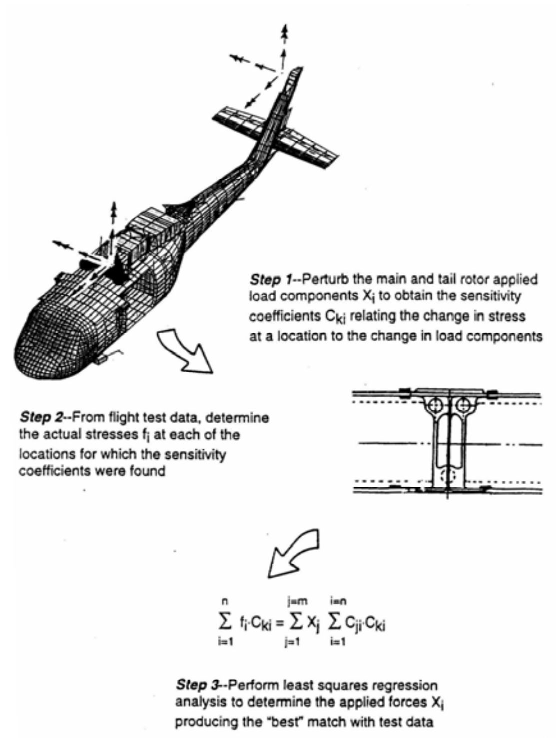

Figure 20 - Regression-Based "Correction" of NASTRAN External Loads

coefficients from a load calibration test, to form a system matrix, which relates each of the external applied force and moment components to the stresses at the strain gage locations. Through a multiple regression error minimization scheme, the applied forces and moments and accelerations, which best produce an analytical response, which minimizes the overall error between the predicted and measured stresses can be determined. These forces and accelerations can be compared against their GenHel equivalents, and adjustments can be made to the GenHel predictions, as necessary.

Similarly, regression analyses can be used for determining the vibratory response of the airframe in each of the structural zones, but; this topic will not be addressed in this paper.

Once the GenHel predictions have been updated and the zonal vibratory response of the airframe determined, the stress histories at each of the fatigue critical locations in the airframe can be regenerated, and the fatigue analyses rerun, if necessary.

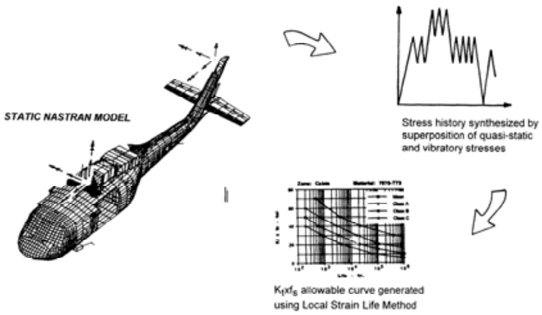

Figure 21 - FEM Fatigue Analysis Process

The Anticipated Benefits include:

- More accurate fatigue life predictions than previously possible.
- Coverage of all fatigue critical locations, including those which could not be gaged.
- Ability to react to new airframe cracking problems, at locations not covered by this effort, without the need for flight testing to establish the local stress history.

SUMMARY

A significant number of cracks (2588 total) documented in field records of 650 US Army and 60 USAF H-60 variants over a 21 month period has increased operating and support cost. This flight test program accomplishing 65 productive flight hours and utilizing 367 sensors has provided a solid technical database. This database will be used for improving analytical tools and structural design models needed to define fatigue strength enhancements. When incorporated, these modifications will insure substantial airframe service life extension. The conduct of this joint USAF / ADF flight test program worked well, it was *a cost effectiveness winner.*