C-5A Active Load Alleviation System

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Several forms of wing load reduction systems have been investigated for use on the C-5A C-5A for the purpose of reducing static loads and/or improving the fatigue life of the wing. A passive system presently is used on the C-5A fleet to provide reduced static wing bending moments for improved payload/gross weight capabilities and to improve wing fatigue life through reduced mean stresses. A fully active maneuver and gust load reduction system has been developed and flight tested and is being incorporated on the C-5A force at present. This system was developed for the specific purpose of providing a significant wing fatigue life improvement through reduction of maneuver and gust-induced incremental wing bending moments. This paper reviews the evolution of the present load-alleviation system (termed ALDCS for active lift distribution control system) and presents a brief description of the system and a simplified functional block diagram. Comparisons of analytical and flight-test-measured maneuver and continuous turbulence loads are shown. The effects of load changes on fatigue damage rate predictions are discussed, with particular emphasis on the implications of multiple-load component changes, i.e., reduced bending moments and increased torsional moments.

Nomenclature

CADC	= central air data computer
g	= gravitational acceleration constant, 32.2 fps^2
GW	= gross weight
H.Q.	= handling qualities
IWBRS	= inner wing box rib station
K	= fatigue quality index
L.T.	= load transfer
MLDCS	= maneuver lift distribution control system
PLDCS	= passive lift distribution control system
SAS	= stability augmentation system
S/L	= stress-to-load ratio
SSF	= stress severity factor
T/H	= time history
δ_a	= aileron deflection
δ_e	= elevator deflection
σ_{MX}	= rms bending moment
A_{HV}	= ratio of test coherent rms response to rms gust velocity
A_V	= ratio of analytical rms response to rms gust velocity
F_{ax}	= axial stress
F_{pk}	= apparent peak stress
F_S	= shear stress
K_A	= aileron gain
K_e	= elevator gain
K_{ep}	= pitch column position gain
$M_{X_{xxx}}$	= bending moment at wing station *xxx*
$M_{Y_{xxx}}$	= torsion at wing station *xxx*
N_Z	= load factor along vertical (Z) axis
N_{Z4}	= fuselage vertical acceleration
$NZ_{RF,LF,RR,LR}$	= right (left) front (rear) beam vertical acceleration
V_e	= equivalent airspeed

Introduction

SEVERAL versions of "load alleviation systems" have been evaluated during the C-5A program. These ranged from analytical state-of-the-art studies to prototype hardware/flight-test programs and involved structural load-reduction goals for both static load alleviation and fatigue endurance improvement.

The present active control system for the C-5A is identified as an active lift distribution control system (ALDCS), the name having been derived from the fact that symmetric aileron deflections are employed as a primary means of providing reduced wing bending moments through modification of the wing spanwise additional lift distribution. The ALDCS program has progressed through a design/development and test phase and a production system design/fabrication phase, and hardward presently is being installed on the force aircraft. This system was developed for the specific purpose of providing a significant wing fatigue life improvement through reduction of maneuver and gust incremental wing bending moments.

The sections that follow provide a review of the various load-alleviation systems that finally evolved into the present ALDCS, definition of the basic mechanization features of the system, comparisons of analytical and flight-test-measured loads and system response parameters, and discussions of the analytical problem of assessing the effects of changes in multiple-load components on fatigue endurance. Comparisons are shown of analytical wing fatigue damage ratios (ALDCS-on/ALDCS-off) for maneuver and gust load sources as derived by a conventional uniaxial damage analysis and by a load transfer analysis method.

System Evolution

The various load alleviation studies and the several design, hardware-development, and flight test programs, conducted at the Lockheed-Georgia Company since 1967, have been accomplished with different objectives in mind: 1) development of analytical methods and technology substantiation, 2) "static" load reduction for gross weight/cargo capability increases, and 3) fatigue load reductions for increased airframe fatigue endurance. More detailed descriptions of these studies and programs, including design objective statements and typical analytical results, are contained in other publications.[1,3,4]

The finalized system (the ALDCS) was developed using the aforementioned analysis methods and technology and incorporates some features of each of the previously developed systems to accomplish the multiple objectives of "static load" reductions and reduced fatigue loads. The following subsections provide a brief summary of the various system studies and development programs.

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LAMS

The Lockheed-Georgia Company participated in the aircraft load-alleviation and mode stabilization (LAMS) program by providing C-5A data to demonstrate the applicability of the analysis methods and techniques to another large flexible airframe. Although the LAMS C-5A system analysis and synthesis was based on a single flight condition, the results concluded that a LAMS type of control system could reduce structural fatigue damage rates during flight through turbulence without degradation of basic aircraft stability and handling qualities.

MLDCS

During the conduct of the C-5A static test program in mid-1969, it became apparent that some form of wing maneuver load control system was needed for the purpose of reducing wing maximum upbending load magnitudes at limit design conditions: a "strength design" load reduction rather than a fatigue load-reduction goal. A study was conducted of various means of obtaining the desired limit load reduction, with an active aileron/inboard elevator concept being selected as the most practical means of obtaining significant wing bending moment reductions with minimum hardware change/least performance penalties.

Since it was desirable to reduce only maximum upbending moments for "static strength" purposes, the concept evolved into a semiactive system, a deadband below 1.5-*g* maneuver load factor keeping the system inactive and thus precluding undesirable control transients and drag penalties during normal operations. This system was developed and flight-tested[2] during late 1969 and early 1970.

PLDCS

A simplified version of the maneuver load control system known as the passive LDCS (fixed aileron uprig position selectable by the flight crew) was chosen for force incorporation, since it not only would provide the desired "static" limit load reduction but also would produce reduced 1.0-*g* wing bending moments and thus would provide a significant improvement in analytical fatigue life. In addition, it could be made operational with minimum hardware changes and did not involve additional "black-box" control inputs independent of the flight crew.

ALDCS

The results of the C-5 wing fatigue test program, during the 1970-1972 time period, indicated a need for further wing load reductions or, more appropriately, wing stress reductions, during both turbulence and normal maneuvering. This need resulted in the present ALDCS program, which was explored initially by the C-5A Independent Structural Review Team (IRT) as an out-growth of the previous LAMS work. Development of an ALDCS and fleet incorporation was recommended by the IRT in its report to the U. S. Air Force.

ALDCS: System Description

The ALDCS provides symmetric aileron and inboard elevator deflections as a function of vertical acceleration, pitch rate, control column position, and airspeed/Mach number. Surface command signals are generated by the ALDCS computer and are fed through the existing SAS computers and primary servoactuator system. The system interfaces with existing control surfaces, actuators and servos, modified SAS and CADC, and new hardware, as illustrated in Fig. 1.

Specific design requirements and criteria[3,5,6] relative to structural loads, system stability, flight control subsystems, and handling qualities were established during the design process and have been substantiated by ground and flight test results.[7-10] A simplified block diagram of the ALDCS, illustrating the essential mechanization features of the system, is shown in Fig. 2. The system is a fail-safe, dual-channel

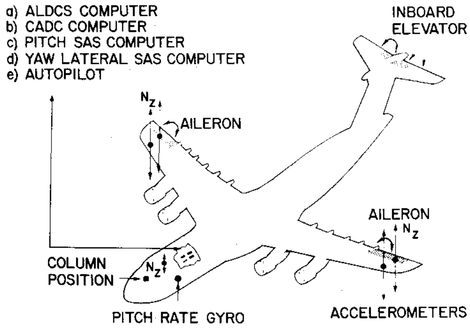

Fig. 1 ALDCS system components.

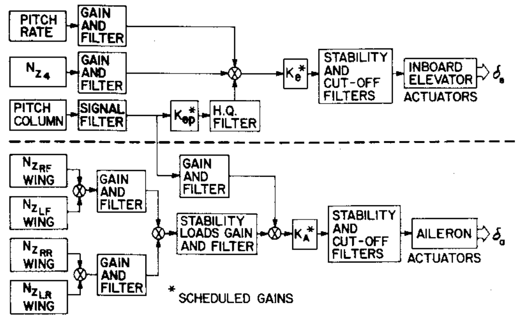

Fig. 2 ALDCS simplified block diagram.

design and operates "full time" within the normal operating speed altitude envelope. Initial design requirements specified system off during flaps-extended operations; however, the present configuration has been substantiated for operation from pretakeoff check to after landing.

The ailerons and inboard elevators are operated through the existing lateral and pitch stability augmentation system using existing surface actuators and control servos. The pitch rate input provides a pitch damping function to reduce continuous-turbulence low-frequency response. The elevator control column position input provides a nulling effect when pilot-induced maneuvering commands are present. The wing-mounted accelerometers provide input commands to the ailerons for suppression of first wing bending response and for direct maneuver bending moment reductions. The elevator position input to the aileron channel provides a "stick-quickening" function to alleviate abrupt-maneuver wing loads. The fuelage accelerometer provides a pitch compensation function to counteract aileron pitching moments.

Analytical/Flight Test Data and Comparisons

Although the ALDCS flight test program included flying qualities, stability and control, failure effects, and other non-structural testing, this paper will discuss only the structural load aspects of the program. The following subsections provide representative samples of typical analytical/test comparisons.

Structural Response to Forced Inputs

Symmetric aileron and elevator frequency sweeps were performed during the test program to establish system stability and frequency response characteristics. Figure 3 illustrates the dramatic reduction that the ALDCS makes in the wing first bending frequency response. Test runs were made both for frequency sweeps and for constant frequency inputs, primarily in order to establish well-defined resonance curves. The ALDCS was designed for minimum control response at frequencies above about 1 Hz. This was due to 1) the desire to use existing servos and actuators, which have a rapid rolloff at frequencies above 1 Hz; and 2) analytical results that show little to be gained, in the way of gust load alleviation, at higher frequencies.

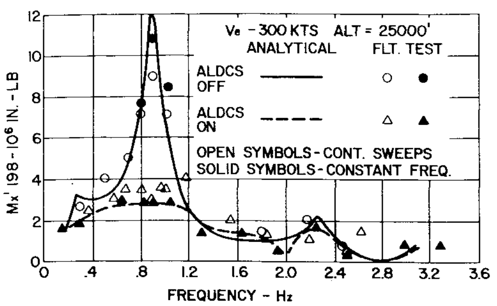

Fig. 3 Wing bending response: frequency sweeps.

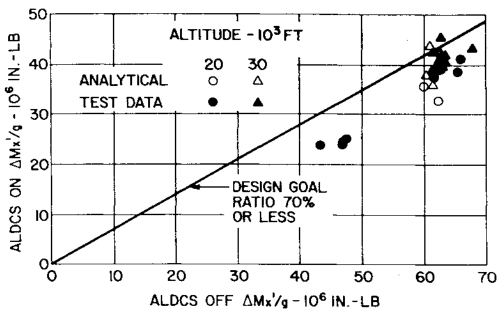

Fig. 4 Maneuver loads: W. S. 198 bending.

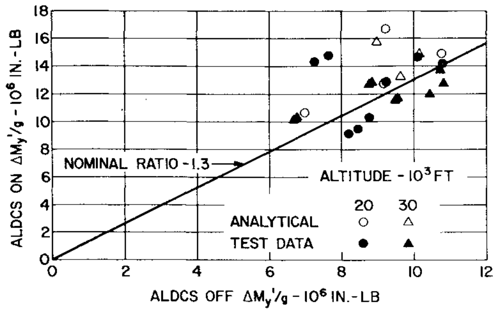

Fig. 5 Maneuver loads: W. S. 198 torsion.

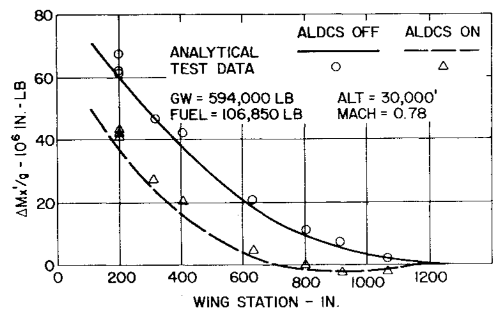

Fig. 6 Maneuver loads: spanwise bending.

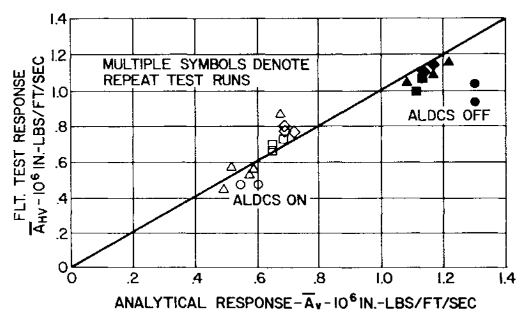

Fig. 7 Normalized gust response: W. S. 198 bending.

Incremental Maneuver Loads

Significant reduction in wing incremental maneuver bending moments results from the aileron modification of the spanwise additional airload distribution. Figure 4 shows both analytical and flight-test-measured incremental wing root bending moment for ALDCS-off and ALDCS-on conditions. These data illustrate the attainment of a design goal of at least a 30% reduction in wing root incremental maneuver bending moments. The test points cover a Mach number range of 0.54 to 0.78 and represent normal operating airspeeds for the test altitudes.

The use of ailerons to provide maneuver incremental bending moment reductions results in significant increases in positive torsion. No criteria were established for torsion load magnitudes, since attainment of the design goal of a 30% reduction in bending moment was considered of prime importance, and the aileron required to produce that reduction automatically produces an increased torsion moment. Figure 5 shows incremental wing root torsion for ALDCS-off and -on. The test-measured torsion loads show generally less torsion increase due to ALDCS than the analytical conditions. In general, wing root incremental torsion increases due to ALDCS are approximately 30% for maneuvering flight conditions.

The effect of ALDCS on the spanwise distribution of incremental maneuver bending moment is illustrated by Fig. 6. This condition is chosen to illustrate spanwise loading effects, since the Mach number of 0.78 is typical of normal cruise conditions, although a test altitude of 30,000 ft is slightly below cruise altitude for the test condition gross weight. The other test condition spanwise incremental bending moment comparisons are similar and show equally good correlation.

Gust Loads

Load reductions during continuous turbulence are achieved both from the ALDCS aileron response and from the reduction in rigid body and short-period airplane response due to the inboard elevator pitch damping action. The design goals for gust load alleviation, simply stated, are at least a 30% reduction in rms root bending moment response with no more than a 5% increase in rms root torsion response. The design of the ALDCS aileron and inboard elevator input signals and gains/filtering provided the desired balance between aileron-generated direct lift modifications and elevator-controlled angle-of-attack response reductions.

Summary plots of wing root bending moment and torsion response are shown in Figs. 7 and 8. Normalized responses (rms loads divided by rms gust velocity) for several test conditions of varying airspeed (235 to 325 knots), altitude (5000 to 15,000 ft), fuel weight (80,000 to 250,000 lb), and cargo (90,000 to 110,000 lb) are included in these summaries. These comparisons are based on symmetric response only, since any unsymmetrical responses are common to both ALDCS-off and ALDCS-on configurations. The analytical $\bar{A}_V$ values result when the analytical model is subjected to the test-derived vertical gust velocity profiles and normalized by the rms vertical gust velocities. The test $\bar{A}_{HV}$ values are the correlated test responses rather than the total test responses, i.e., the responses that are coherent with the measured normalized vertical gust inputs.

Figure 7 illustrates good analytical/test agreement and clearly shows the significant reductions (30-50%) in wing root bending moment response with ALDCS-on. Figure 8 shows generally good analytical/test agreement for root torsion and illustrate the relatively small change in gust induced torsion loads with the ALDCS-on.

A spanwise bending moment analytical/test comparison with ALDCS-on is shown in Fig. 9. The results of five runs for one set of test parameters are shown and illustrate the typical scatter inherent in dynamic response test program results. Three of the five runs show excellent agreement between test-derived $\bar{A}_{HV}$ and analytical $\bar{A}_V$ bending moments

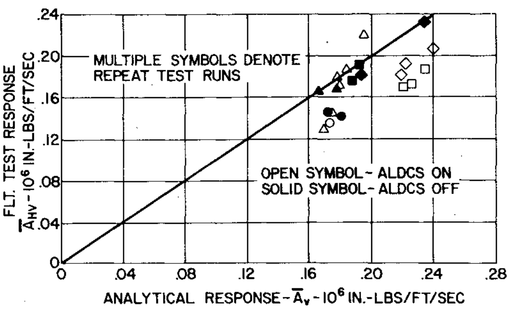

Fig. 8 Normalized gust response: W.S. 198 torsion.

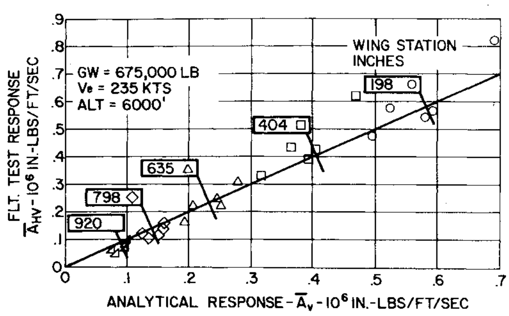

Fig. 9 Normalized gust response: spanwise bending.

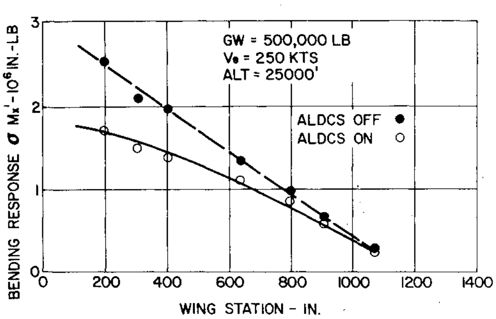

Fig. 10 Wing bending response: in-flight refueling.

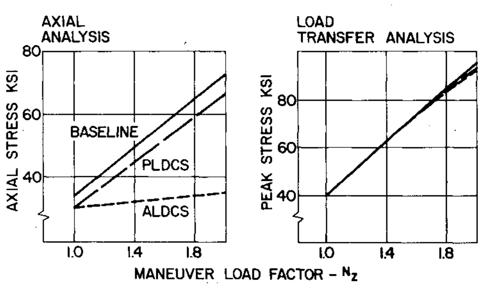

Fig. 11 Analytical maneuver stresses: cap/web splice.

at each of the seven instrumented wing stations. The one run showing significantly greater test response and poorer agreement had a measured input gust spectrum that was more irregular than the other runs, particularly at low frequencies, the region of the gust spectrum containing the predominant gust power. The run showing significantly lower response values than the average also had a rather irregular gust input spectrum, with reduced amplitudes at the lower frequencies.

In-Flight Refueling Response

Although no criteria, relative to in-flight refueling load reductions, were involved during the system design process, it was desirable to identify the load modificationd due to the ALDCS during this type of operation. Figure 10 provides a spanwise bending moment response comparison as obtained from ALDCS-off and -on dry hoodups. This plot is a composite using data from several flights. The gross weights varied from about 502,000 to about 589,000 lb, with fuel/cargo weights varying slightly during the various test runs. A total of three runs ALDCS-off and four runs ALDCS-on are included in the combined data. Wing torsion responses showed slight changes due to ALDCS: some reductions and some increases, dependent on wing station. In general, the data look much like the continuous turbulence response data.

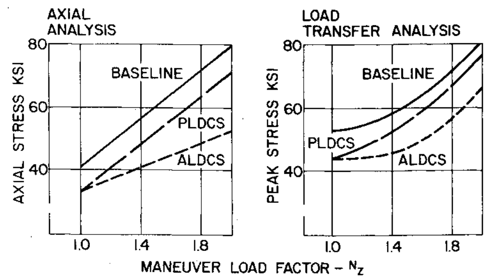

Fig. 12 Analytical maneuver stresses: spanwise splice.

Fatigue Endurance Considerations

The assessment of the effectiveness of any load alleviation system, with respect to increased fatigue endurance, requires an analysis methodology that addresses the effects of the total loading spectrum as affected by the load-alleviation system. Since the C-5A load-alleviation system was developed as an "add-on" to an already existing structure (which has well-defined loading characteristics, test-substantiated stress-to-load relationships, and cyclic test-derived quality index values), the question of what to do about changes in shear stress as well as axial stress must be addressed. This is particularly true when using the classic approach to fatigue analysis, i.e., use of Miner's rule and constant-amplitude S/N data in a system that deals with a singularity stress state.

Axial vs Load Transfer Analyses

An analytical method, which accounts for shear stress effects in addition to axial stresses in mechanically fastened, single shear lap joints, is available and has been applied in the evaluation of C-5A cyclic test results. This method is basically a stress severity factor method, as reported by Jarfall,[11] which has been modified to account for fastener load-transfer effects in a lap shear joint. By definition, the stress severity factor is the ratio of peak stress at the edge of a fastener hole to the gross area uniaxial reference stress. The resulting analysis method, including correlation of analyses to test data, has been presented previously[12] and will be referred to subsequently as a load-transfer analysis.

Application of the load-transfer analysis to a beam cap to web splice and to a lower surface spanwise splice on the C-5A wing illustrates the significance of changes in external load characteristics on apparent peak stresses at the edge of fastener holes. Figures 11 and 12 show the variation of axial and peak stresses with maneuver load factor for the aforementioned representative structural locations. External loads for the baseline airplane configuration and the PLDCS and ALDCS configurations for a representative speed/altitude/mass configuration maneuver load condition were analyzed using axial and load-transfer methods. These analyses used test-derived stress-to-load ratios, baseline configuration quality index values (K's), and necessary analytical structural parameters such as fastener tilt factors, hole bearing stress concentration factors, etc. The analysis results for the beam-cap-to-web location (Fig. 11) provide a graphic illustration of the potential inadequacy of relying on an axial stress analysis using test-derived data from one aerodynamic configuration to evaluate the effects of changes in aerodynamic configuration (external load characteristics).

This particular structural location shows no apparent improvement (reduction) in stress level due to ALDCS when using the load-transfer analysis for this particular load source (maneuver). The implication here is simply that the axial stress reduction due to reduced bending moment is obviated by the increase in shear stress due to amplified torsion loads. This appearent equal tradeoff between reduced bending moment and increased torsion will vary with other structural locations (Fig. 12) and with specific mission segments (variations in cargo weight, fuel weight, airspeed, and altitude) and load sources (maneuver, gust, etc.).

Gust Loads/Stress Time History Analysis

In an attempt to define the possible net analytical effects of gust loads/stress phasing relationships on peak stresses, the load-transfer procedure is coupled with a loads/stress time history solution, as illustrated by Fig. 13. Analytical and test-measured shear, bending moment, and torsion load time histories are used to generate axial and shear stress time histories at selected structural locations. Then, discrete time points are analyzed using the load-transfer equation to generate peak stress time histories.

The relationships between peak stress and axial stress (in actuality, the discrete values of stress severity factor at each time increment) may be studied by plotting peak stress vs axial stress for each time increment, as illustrated in Fig. 14. These data are the result of application of the procedure just discussed to flight-test-measured shear, bending moment, and torsion time histories as measured during successive runs through the same nominal turbulence field. The ALDCS-off and ALDCS-on measured loads were normalized to the same rms gust intensity (8.66 fps) by a simple σ gust ratio process, since the test-derived vertical gust spectral shapes were quite similar, and the individual run rms gust intensities were within 12% of one another.

As mentioned earlier, each time history point represents a discrete stress severity factor; however, the general variation of peak stress with axial stress may be defined in a gross manner by a simple slope that passes through the 1.0-g point. As illustrated, the axial stress excursions show a significant reduction. The overall effect, for this example, is an approximate 27% reduction in σ peak stress at this particular structural location for the continuous turbulence load source that existed during the sample test runs.

The load-transfer stress severity factor equation is of a nonlinear nature, since the bearing stress term always produces a tension stress at the edge of the fastener hole, regardless of the sign of the shear term. It is apparent that the peak vs axial stress time history nominal slope procedure produces a linearized approximation to whatever nonlinear effects result from the load-transfer analysis; however, the peak stress vs axial stress plots provide a more well-behaved data base from which to proceed than would the more conventional external load time history variations such as bending vs torsion or shear vs torsion.

The load-transfer analysis appears to be a valuable analytical tool for assessing the effects of changes in external loading characteristics, provided that a resolution of the PSD loads/stress phasing problem can be accomplished. A development program presently is underway at Lockheed-Georgia Company along the lines outlined in the foregoing discussion. Meanwhile, a thorough analytical evaluation of the fatigue life improvement attributable to the ALDCS is limited to uniaxial analysis results or a load-transfer analysis with assumed load/stress phasing.

Fatigue Damage Rate Comparisons

Although well-substantiated estimates of total fatigue endurance changes due to ALDCS are not available at the present time, because of the limitations of the available analysis methods as discussed in the previous paragraphs, evaluations can be made of maneuver and gust source damage rates for conditions where flight test data are available. Use is made of the load transfer/stress time history procedure to derive stress severity factors for ALDCS-off and ALDCS-on configurations for several structural locations. Damage rates then are calculated using the SSF values as "effective quality index values" in a conventional axial fatigue analysis. Additionally, the same conditions are evaluated using the baseline configuration fatigue test-derived K's, for both ALDCS-off and -on, in a conventional axial analysis.

Damage rate ratios are shown in Figs. 15 and 16 for three inner-wing, lower surface structural locations for gust and maneuver load sources for a selected flight test condition. The

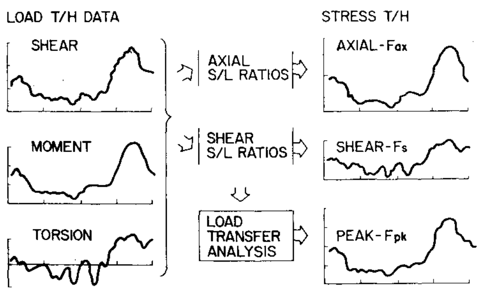

Fig. 13 Stress time history generation.

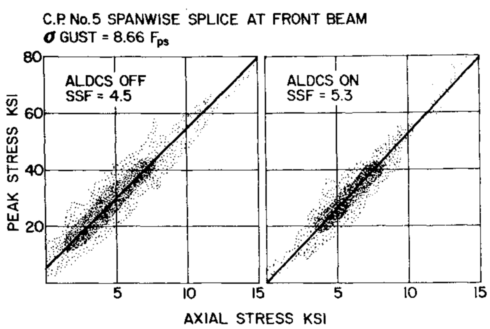

Fig. 14 Peak stress/axial stress histograms.

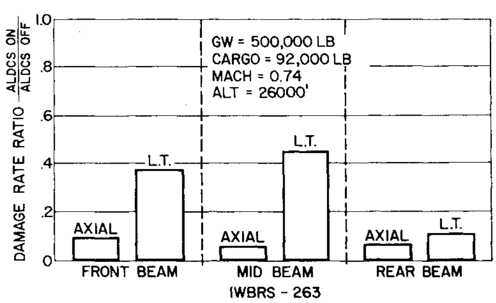

Fig. 15 Gust damage rate ratios.

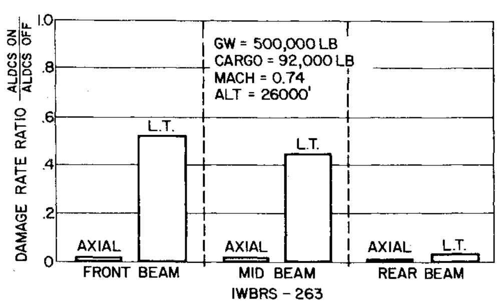

Fig. 16 Maneuver damage rate ratios.

gust environment and maneuver load factor spectra are normal design criteria, the flight test data being used only to define the stress severity factors for the load-transfer gust damage analysis. The large variations in damage rates between the two methods of analysis are illustrated clearly. Figure 15 shows an ALDCS gust damage rate improvement of between 1 and 10, depending on the analysis method used. The strong influence of shear stresses, as accounted for by the load-transfer method, is well illustrated by the front and midbeam location ratios.

The maneuver damage ratios of Fig. 16 provide an even more graphic illustration of the influence of shear stresses on analytical damage using the load-transfer analysis. For maneuver conditions, a significant increase in positive torsion occurs with reduced bending moments, as shown in Fig. 5. This results in relatively high damage ratios at the front beam and low ratios at the rear beam.

These figures illustrate the relative ALDCS improvements that may be expected in maneuver and gust source damage rates for a typical flight segment. A complete analysis of the effects of ALDCS on total life improvement for a typical set of mission profiles and utilization rates, using the load-transfer analysis, cannot be performed at the present time because of the aforementioned load/stress phasing problem; however, the preliminary work accomplished using the flight test time history analysis indicates that significant reductions in overall damage rates may be expected. A conventional axial analysis, using the baseline configuration test-derived K's for both ALDCS-on and -off, indicates life improvement factors on the order of 25 to 50%, depending on structural location. Detailed results of axial analyses and limted load-transfer analyses of flight test conditions are contained in Ref. 13.

Conclusions

The analytical and test data generated during the C-5A ALDCS development and test program provide a basis for the following conclusions:

1) The maneuver and gust load test data substantiate the analytical load methods and provide a solid base from which to develop ALDCS life improvement estimates.

2) Uniaxial stress/fatigue analysis methods may result in overoptimistic predictions of fatigue endurance improvement due to load alleviation systems as a result of favorable changes in axial stress, but not accounting for significant changes in shear stresses.

3) The load-transfer method provides an analytical means of accounting for changes in shear as well as axial stresses.

4) A complete fatigue analysis, using the load-transfer method, is limited by the assumptions or methods used to define the load/stress phasing relationships of PSD-derived loads.

5) The time history analysis method discussed herein provides one possible solution to the PSD load/stress phasing problem.

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