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Stretched C-141: Cost Effective Application of Structural Technology

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In 1973 it became apparent that the C-141 aircraft was range and volume limited. Lockheed made an unsolicited proposal to "stretch" the C-141A and add aerial refueling capabilities. The "stretch" was accomplished by adding two plugs totaling 280 in. This allowed the loading of 13 rather than 10 pallets. The USAF and DOD liked the idea and in 1975 a "stretched" C-141 became the first in a series of steps to increase our nation's airlift. The user had one major concern: Don't degrade the service life of the aircraft! The Aeronautical System Division (ASD) and Department of Defense (DOD) had another concern—Is the airframe capable of operating past the service life of 30,000-40,000 flight hours? The DOD had one further admonition: Hold down the cost. This paper relates how structural technology was applied to minimize the modification cost and demonstrates that the durability and damage tolerance of the airframe is adequate for a viable modification. Some interesting insights are revealed by examining the design/produce-to-cost effort.

Concept‡

Constraints and Solutions

FROM congressional studies in early 1973, it became apparent that increases in strategic airlift were necessary, particularly to maintain U.S. NATO commitments. The USAF and DOD sought and defined a number of successive alternates to accomplish the necessary increases. One of the earliest, least expensive, and innovative concepts was to gain a 30-50% increase in cargo space and, therefore, airlift capability by stretching the existing force of 274 C-141A aircraft. The concept had several constraints but each had a solution, as shown in Table 1.

New Aircraft, New Engine vs Stretch

With the 23.3-ft extension concept, the preliminary design studies proceeded, looking at other alternates illustrated in Fig. 1. Since we had excellent cost history data, it was relatively simple and comparatively accurate to compare the modification aircraft to its equivalent value in terms of new aircraft using current inflation factors. The productive increase was predicted to be 35%, which equated to 90 new aircraft of the size of the C-141A.

Use of a longer plug was also studied, but added substantially to the cost, owing to problems with more complicated tooling, additional beef-up, and flap and gear modification to clear the ground.

We estimated these aircraft could be purchased at a cost of 1.4 billion 1975 dollars; i.e., about $16 million per aircraft. This, compared to the cost of modifying the aircraft—$332 million, made the modification very attractive in terms of increased capability at the lowest cost.

During the conceptual phase, studies were made to purchase newer, fuel-efficient engines for the new aircraft in lieu of procuring the existing TF33-P-7 engines. The study indicated $\$173 \times 10^6$ additional for engine procurement cost would be required to save $\$6 \times 10^6$ per year in fuel. The newer engine could not be justified.

At any rate, in concept we believed we were offering the equivalent of 90 new aircraft at a cost of $\$332 \times 10^6$ instead of the $\$1,400 \times 10^6$ it could cost.

Proposal

Airframe Modification

The concept proposed is shown in isometric view in Fig. 2. It was proposed that the wing fillets be removed, the aircraft taken apart just ahead and aft of the wing at fuselage station 734 and station 1058, respectively. These sections bound the center section of the aircraft. Two barrel sections of similar construction would be installed, the forward being 160 in. and the aft 120 in. Gear pod fairings would be reinstalled without having moved relative to the center section. New wing fillets of an advanced configuration would be used which would improve the wing center section airflow. The fillet was reshaped to carry the increased weight without increasing wing bending moment in routine flight ($1g$ and routine maneuvers), moving the wing center of pressure inboard. Bending moment increases on the order of 40-60% occurred in the fuselage centerbody owing to the longer length of the fuselage. The aircraft design retained the block loading design approach to give maximum flexibility in floor loading. While the original fuselage and outer wing had reasonably excessive margins of safety which had never been exploited, analysis indicated beef-up would be required both in the shear and bending capability of the center fuselage. A concept of removing and replacing the centerbody side panels and placing heavy longerons through the dry center wing was adopted.

While the aircraft was stretched, installation of an aerial refueling receiver, largely external to the pressure shell, could be accomplished.§ The wing fuel system already contained a manifold system that could accommodate the incoming fuel with some modification to the valves, vents, and controls and the addition of an external manifold from the wing to the receiver valve.

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‡The value engineering dollars quoted in this paper are estimated for the purpose of measuring relative differences in options, are referenced to 1975 rates and material costs, and should not be confused with actual costs.

§Acquisition costs without aerial refueling: $332,000,000. Acquisition costs with aerial refueling: $372,000,000.

Table 1 C-141 stretch program. Concept: Gain 30-50% in cargo volume and airlift by stretching C-141A aircraft

Constraint	Solution
No increased drag	Add fillet
No decrease in life	Tailor fillet to minimize lift due to stretch weight increase
Minimize cost	Careful application of sound engineering
Confirm fatigue life projections	Conduct DADTA and apply fracture mechanics

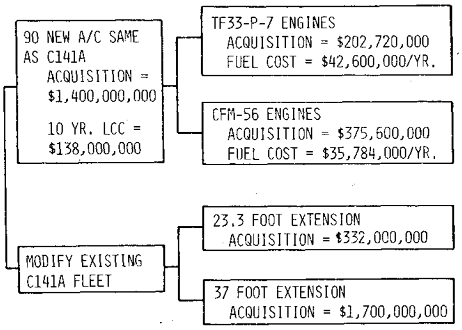


Fig. 1 Conceptual.

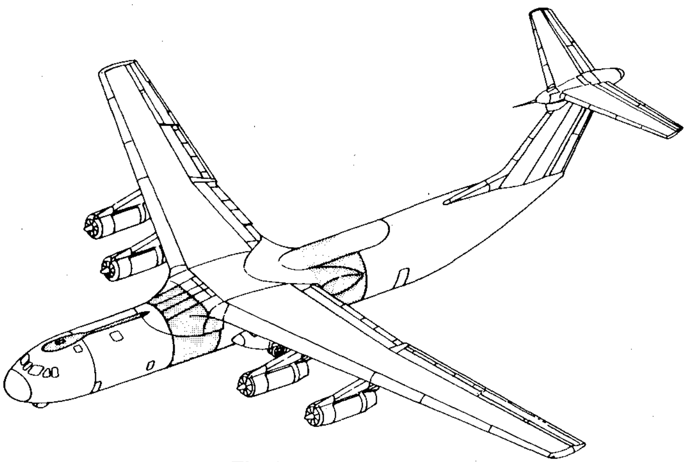


Fig. 2 C-141B.

Mission Requirements

With the increased space, the question is raised as to whether additional troops and/or aeromed evacuees would be carried. Such increases would require additional escape hatches, life rafts, and oxygen provisions in the modification program, also additional life rafts and troop seats, which in the original C-141 program were procured as kits. There was a long-standing desire on the part of Lockheed and the Air Force to improve the heating and air conditioning, which can be described as adequate in the unmodified aircraft; i.e., there was no surplus to accommodate an increase in the volume to be serviced. Military airlift command felt no real increase for additional troops or aeromed patients was necessary, and so specified.

Wing-Fuselage Fillets

Using wind-tunnel data, several sizes and shapes of fillets were compared and costs estimated. A configuration with minimum infringement of the flap and little penetration of the rear beam assemblies of the wing box offered a fillet which was adequate in reducing drag and economically avoided reworking critical structural and other airframe parts.

A fillet, of course, is an insert in the major fuselage-wing intersections to improve flow. On small aircraft. these are built of sheet metal and can be thought of as simple. In case you have that impression, the one proposed is 1100 ft^2; i.e., twice the wing area of the JetStar aircraft, involves 5000 parts, and costs $261,000. A study was conducted to increase the amount of fiberglas and use selected graphite fiber composites to reduce part count and weight and reduce cost. The studies indicated a program cost increase of $9 million, which would not be readily offset by the weight saved in terms of life-cycle costs.

Flush vs External Aerial Refueling Pod

Another study involved the use of a flush aerial refueling pod vs an external pod. Wind-tunnel data indicated less than a drag count for the external pod. Extensive cost would have occurred for the flush mount. Lockheed proposed the external pod at a $4 million savings to the program.

Oil Replenishment

A selection study of the location for an increase in engine oil supply was also conducted which indicated fuselage tank and wing lines would be cheaper than four pylon located tanks.

Service Life—Fatigue Testing

The C-141A was developed with a fully implemented structural integrity program as outlined by ASD TR61-141. Four major components had been tested from October 1964 to April 1969, suggesting 41 modifications, 39 of which were implemented. As of November 1973, specimen A, the fifth specimen, which is a full-fuselage, late-model production wing, was cycling. The specimen had received 1,039,000 cycles of load under a block loading system that retained all ground air ground cycles, 23,550 pressure cycles (p), suggested four modifications (of which all were incorporated in the force), and had demonstrated 51,000 equivalent flight hours on an unfactored basis.

Operational Usage

The question of service life must address how the aircraft is to be operationally limited and used. C-141A aircraft had been cleared to take off at 325,000 lb and to use zero fuel weights up to 204,620 lb. Capability studies indicated flight weight capability of 343,000 lb and zero fuel weight of 239,000 lb at 2.25g based on flight test loads and static test results. The manual permitted 70,000 lb of cargo at 2.5g which with 6000 lb of operating equipment becomes 64,000 lb off the dock. Typically the load off the dock was 4700 lb/pallet or 47,000 lb, indicating the space-limiting nature of the design. Stretching the aircraft was projected to increase the weight 11,000 lb, about 5% of zero fuel weight (ZFW) or 3% of takeoff. Military Airlift Command (MAC) again stepped up to their responsibility and quickly stated they needed no increase in capability for peacetime operations and that the service life decrease in a contingency could be absorbed if the service life was not exhausted owing to peacetime utilization.

Service Life Projection-Fatigue Methodology

The stretched aircraft was analyzed using C-141A peacetime utilizations which came from extensive individual aircraft tracking data and VGH data collected from 1969 through 1972 under Air Force Logistic Command (AFLC) and ASD programs. The cumulative fatigue damage technique with test derived stress concentrations projected a decrease in service life of individual aircraft of up to 39%. While Lockheed believes that the service life of aluminum aircraft is not technically limited with reasonable repair and replacement, and the unfactored fatigue results clearly

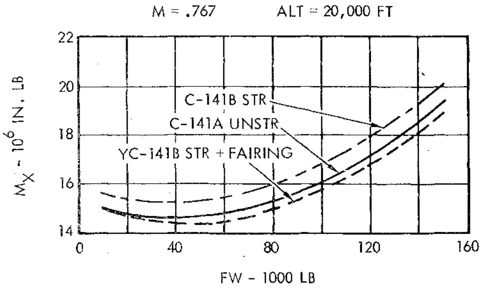


Fig. 3 **Analytical 1.0*g* mean load.**

showed the aircraft life would exceed the original design goal of 30,000 hours, it was not evident that the 40,000 hours necessary to make the modification viable was available. Additional work was done to try to offset the wing bending load increase caused by the small (11,000-lb) weight increase. In decreasing order of complexity, active control, aileron uprig, and reshaping the wing fillet were compared. The fillet reshape gained the load decrease at small loss in the drag improvement but still left a viable modification.

Effect of Fillet

In order to avoid such a life decrease an improved wing-fuselage fairing was developed that would, for equal payloads, maintain the 1.0*g* mean operational loads for the C-141B equal to or less than those for the C-141A. Using wind-tunnel-based data, Fig. 3 presents a comparison of typical cruise wing root vertical bending moment as a function of fuel weight for three configurations, each carrying 30,000 lbs of cargo "off the deck":

1) the C-141A unstretched aircraft at a zero fuel weight of 166,193 lbs;

2) a C-141A stretched aircraft at a zero fuel weight of 174,180 lbs; and

3) a C-141A stretched aircraft with improved fillet at a zero fuel weight of 175,664 lbs.

The C-141B airplane without the improved fairing is analytically shown to have an approximate 1-million-in.-lb increase in wing root bending moment. The effect of adding the improved fillet is to reduce the wing load to levels equal to or less than those for C-141A airplanes. Similar results were obtained for maneuver incremental loads and at other wing stations.

Full-Scale Development Prototype Program

Fly Before You Buy

The proposal was accepted and we entered full-scale development, but not before a Scientific Advisory Board/IRT had been convened and a plan was made to concurrently conduct a durability and damage tolerant assessment (DADTA) of the C-141A aircraft in order to firmly establish through fracture mechanics analysis and test that the required service life could be achieved.

As the structural integrity program for the prototype C-141B was being outlined, some concerns were expressed by the DOD and ASD concerning durability and damage tolerance characteristics of the stretched airframe. Specific questions were asked concerning how much additional usable structural life would exist at the time of stretching the airframe and whether or not this additional life could be considered to extend until the year 2000. These concerns were voiced in an effort to analytically establish the cost effectiveness of the major investment in the USAF fleet of C-141's.

Further, the stretch program was considered of sufficient dollar value that a "fly before you buy" procurement concept was used. Full-scale development in this case means full-scale engineering, but limited tooling and construction and testing of one prototype aircraft before a production decision.

Durability and Damage Tolerance Assessment

The approach to be used in the conduct of the DADTA is straightforward at the overall planning level: identify critical locations, select a crack growth methodology and criteria, establish crack growth times and critical lengths, establish inspection intervals, investigate repairs or local modifications, and establish a plan to maintain service life. Such a detailed plan necessarily establishes an estimate of the dollars to continue flying, which, after all, is the necessary data required to establish the economic life.

Sounds simple, but there are a number of the decisions relative to the structural technology. The decisions were joint Air Force/Lockheed decisions. There was on-site participation by personnel from the Warner Robins Air Logistic Center (WR-ALC) and ASD structural engineering and a strong USAF steering committee that provided program direction at regular intervals (roughly 60 days). The decisions form an excellent technical basis for providing a safety-oriented force management data base and addressing a number of structural technology questions.

In the crack growth concepts of MIL-A-83444, it is presumed that initial flaws exist in the structure owing to manufacturing irregularities. The fracture mechanics analysis used in the calculation of initial and recurring inspections is based on analytical growth from the safety-based assumed flaw sizes. The larger safety-based assumed initial flaw sizes are used in establishing safety inspection requirements, while the smaller values or equivalent initial flaw sizes are applicable to the durability or small flaw growth times.

Teardown Inspection

Where do you go to determine critical locations? Teardown of high time, highly utilized flying articles from the force is probably the best answer. The Warner Robins Air Logistic Center, with Lockheed's help, maintained excellent records on service problems through analytical condition inspections, regular Program Depot Maintenance (PDM) and detailed investigation when problems occurred in MAC's operation. No teardown work had been done. No crash or accident had provided salvage hardware which could be used.

Teardown work was initiated on several C-141A full-scale fatigue test specimens. Approximately 3000 fasteners were removed principally from the wing structure. The joints were carefully inspected and reassembled. Selected cracks were removed for fractographic studies. Selection of critical locations for analysis proceeded parallel to the teardown work, relying on previous stress and fatigue analyses; fatigue test results; and strain surveys from both static and fatigue testing and service experience. Also considered in reviewing the design was inspectability and the manufacturing assembly technique.

Teardown provides a detailed look at the structure to see if small cracks, not previously discovered in testing, exist. When small cracks exist, it is possible that the initial flaws can be identified. If not, knowing the crack length and loading history on the article may permit an equivalent initial flaw to be determined analytically.

The teardown effort did not identify any new areas of concern but did provide some insight into where the construction was good, better, and best.

Identification of Critical Areas

The overall screening of primary airframe structure is necessary in order to establish a list of structural locations that are considered significant in evaluating the damage tolerance characteristics of the airframe. Three hundred fifty-one locations were selected after a thorough study of all available information concerning full-scale static and fatigue testing; flight testing; service experience concerning corrosion and cracking locations; a review of the inspectability characteristics of the various structural configurations; and an evaluation concerning the manufacturing and assembling techniques used in construction, as well as a thorough review of all engineering reports of the basic loads and stress analysis of the airframe. After establishing a screening process considering all of the above factors, the major components of the airframe such as wing, empennage, and fuselage are subjected to a final screening from which 76 candidate areas for analysis were determined. This final selection of analysis points is intended to represent a composite of significant structural regions of the airframe from which a safety program of initial and recurring inspections can be formulated, not just at the detailed area but over the bulk of the airframe.

Slow Crack Growth Analysis Criteria Selected and Developed

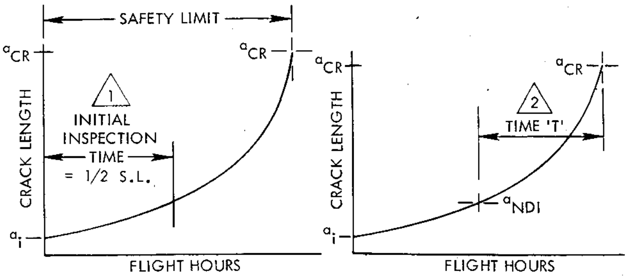
A DADTA program is an analytical program which is structured to provide a safety basis for conducting initial and periodic inspections on representative regions of the primary airframe structure. It is based on the premise of assuming the presence of an initial defect or flaw at each of the selected structural analysis locations. Based on the presence of an assumed initial flaw, a crack is allowed to analytically grow or extend under the influence of the stresses at that particular structural location. For safety reasons, initial inspections are begun for all aircraft at an early enough time to allow ample opportunity to detect the growth of a rogue or worst flaw before the crack reaches a critical length. Critical length is defined as a length where limit load would produce unstable growth in the particular part. Through a combination of nondestructive inspection (NDI) techniques and calculated growth time, the recurring inspections were then established. It is necessary to establish an analysis criteria so that uniform procedures and results can be calculated and displayed in a final matrix format for review by the Air Force for implementation considerations. Such a procedure employs the rate of growth of the crack to allow time for discovery before the particular part at the location being investigated can reach a critical length. A further level of safety may exist at the time of a part failure in the form of a fail-safe or residual load capability. It was elected to use the slow crack growth approach as being easier to apply and probably more conservative than a fail-safe approach.

Inspection Criteria

The combination of analytical crack growth curves as well as the NDI crack detectability considerations form the basis for establishing recurring safety inspection intervals. The initial inspection at a given structural location is recommended to be conducted at a time in flight hours equal to one-half the total safety limit time. The recurring inspection is recommended at an interval one-half the amount of time needed for the assumed crack to grow from an NDI maximum undetectable crack size to limit load critical size. As the NDI methods can be varied and each method will have an associated maximum undetectable crack size, it is hoped that the recurring inspections can be varied accordingly and structured to fit into planned inspection programs in the Air Force maintenance schedules. Highly stressed areas of the airframe may require recurring intervals at other than normally planned periods and these can be reviewed and placed at appropriate action points. Figure 4 illustrates the recommended methods of calculating initial and recurring inspections. After reaching this point in the DADTA program, it was possible to collect all of the inspection recommendations in a matrix format against each of the structural locations and explore a force management plan for the aircraft.

Typical Matrix

Figure 5 shows a typical part of the matrix developed. At areas identified by previous testing, experience, and the assessment of other analytical information, the inspection times were established, an estimate of the number and extent of repair action was made, and total cost forecast. The inspect and repair option was often compared to making some earlier repairs. While the dollar costs are value engineering estimates and may escalate with time, the information does indicate the practicality of maintaining the aircraft in service, and allows the alternates to be evaluated. Several actions indicated at 20,000 hours are now being conducted in the Depot Maintenance Cycle and others at Lockheed in conjunction with the stretch program.



INSPECTIONS

- INITIAL

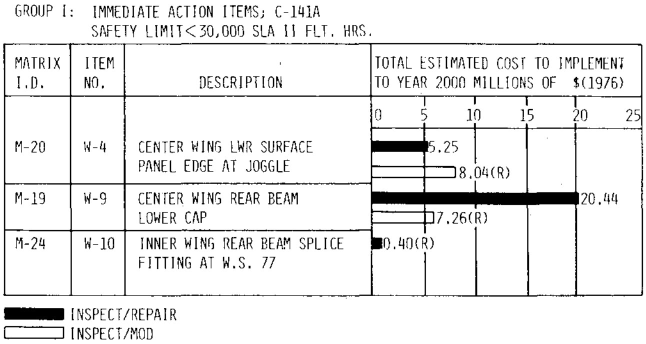
△1 INSPECT AT 1/2 THE SAFETY LIMIT

- RECURRING

△2 PERFORM RECURRING INSPECTIONS AT 1/2 THE TIME 'T' (F.H.) FOR A CRACK TO GROW FROM THE MAXIMUM UNDETECTABLE CRACK SIZE (E.G. a_{NDI}) TO AN UNSTABLE LENGTH AT LIMIT LOAD (E.G. a_{CR}).

SAFE-USE INTERVALS OF OPERATION CAN CONTINUE UP TO AND PAST THE CALCULATED SAFETY LIMIT (FOR A SPECIFIC STRUCTURAL COMPONENT) PROVIDED NO CRACKING IS DETECTED AT THE TIME OF RECURRING INSPECTION.

Fig. 4 C-141A DADTA criteria.


GROUP I: IMMEDIATE ACTION ITEMS; C-141A
SAFETY LIMIT<30,000 SLA II FLT. HRS.

MATRIX I.D.	ITEM NO.	DESCRIPTION	TOTAL ESTIMATED COST TO IMPLEMENT TO YEAR 2000 MILLIONS OF $(1976)
			0 5 10 15 20 25
M-20	W-4	CENTER WING LWR SURFACE PANEL EDGE AT JOGGLE	5.25 8.04(R)
M-19	W-9	CENTER WING REAR BEAM LOWER CAP	20.44 7.26(R)
M-24	W-10	INNER WING REAR BEAM SPLICE FITTING AT W.S. 77	0.40(R)

■ INSPECT/REPAIR
□ INSPECT/MOD

Fig. 5 C-141 DADTA cost estimates (apply to C-141A or C-141B).

Durability Estimates

In addition to conducting the safety-based calculations, it was also necessary to predict the durability indicators for the airframe. The durability characteristics are determined from a smaller assumed initial flaw size (0.005) than those of the safety-based calculations (0.05). The principal analytical elements used in establishing the durability characteristics of the C-141 were developed from the C-141 full-scale fatigue test articles, specimen A and specimen B.

Figure 6 illustrates various values of analytically backtracked equivalent initial flaw sizes (a_i) calculated using crack growth analyses and fractographic analyses from cracked specimens. The various sizes (or values) of equivalent initial flaws illustrate that there is a dependence on structural configuration and structural location. Also shown in Fig. 6 is the final crack size (a_f) found on the actual test article. The full-scale fatigue test article, specimen A, provided the data from which the durability-related values were calculated.

A principal investigative task relative to durability was to evaluate the performance of the full-scale fatigue test specimen A; in terms of correlation to flight-by-flight spectrum of loading. The full-scale fatigue test had been conducted using a block arrangement of spectrum loads for the first 90,000 cyclic test hours (CTH) and a major question from the Air Force was what this 90,000 hours of block testing equated to in terms of flight-by-flight testing.

The block vs flight-by-flight correlation required that a basis be developed upon which to make this comparison. The growth times of a wing lower surface spanwise splice crack was selected as the basis for this comparison. In each case a crack was grown from the fastener hole to the edge ligament, first, using the test arrangement of block loads and second, repeating the calculation with the average utilization flight-by-flight stress spectrum. The relationship between these two amounts of time was then used to establish a force-to-test ratio. This analytical study reflected that one flight-by-flight hour was equivalent to roughly two block test hours.

Figure 7 presents the force-to-test ratio concept used at several locations on the C-141 wing. It serves to illustrate that the ratios will vary with location on the structure as well as the crack length interval used in the analysis.

Once the relationship had been established for the wing spanwise splices insofar as a block to flight-by-flight relationship was concerned, it was then reasonable to calculate a life indicator for the wing structure. The wing lower surface spanwise splices were considered to be a principal life-limiting structural configuration.

A second principal factor in establishing durability estimates is the ability to aggressively prevent corrosion during the planned operational life of the C-141. A detailed study was conducted to highlight those areas of the airframe where corrosion-prevention actions were indicated. These were discussed in detail with the Air Force; most of these corrosion-prevention actions were already well underway in the planned force maintenance of the fleet.

At the 90,000-CTH point in the specimen loading history, it was then decided to convert to a resequencing of the test loads to simulate a flight-by-flight arrangement of future loading. This was accomplished and an additional 28,000 flight-by-flight CTH hours were applied to specimen A.

C-141 DADTA Conclusions

It was concluded that a safe plan for managing the force could be developed and would be economical. With such a plan the service life of the C-141A was projected to be at least 45,000 hours based on the implementation of the recommended safety inspections as well as the implementation of an aggressive corrosion-prevention program.

Effect of C-141B Stretch Modification

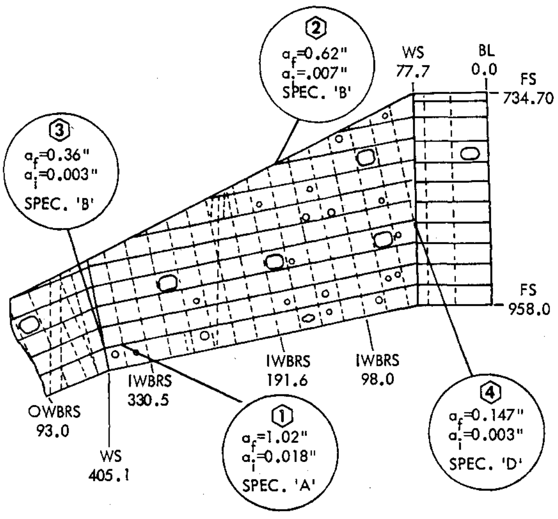
At the conclusion of the C-141A DADTA, it was necessary to evaluate the effect of the added fuselage length and revised missions on the stress levels and to reassess the inspection intervals. The procedure followed was essentially the same in principle as used on the C-141A. The major difference was to include the stress level changes for the small weight changes and the higher stress levels overall in the fuselage centerbody.

At the time of the decision to proceed to stretch the C-141A, the average force flight hours were approaching 20,000 and it was therefore necessary to account for this 20,000 hours of "C-141A" usage as well as for the remaining planned usage in the C-141B configuration. This accounting of dual utilization required that the crack growth curves reflect both A and B characteristics.

The crack growth calculations were conducted for each of the selected structural locations, and initial and recurring inspections were determined. Some inspection intervals lowered slightly but the number of inspections projected did not change and the durability exceeded the 45,000 hour goal.

Detail Design and Structural Optimization

The center fuselage beef-up to provide the additional vertical bending capability required for the lengthened fuselage was one of the major decision items that provided significant savings in cost, weight, and manufacturing time during the C-141 stretch program. Figure 8 shows the baseline beef-up design as originally proposed. The baseline called for



ITEM	DESCRIPTION
①	IWBRS 360. R.H. UPPER SURFACE SPANWISE SPLICE - OUTER TAB
②	FRONT BEAM, R.H. UPPER CAP CRACK @ PANEL #9 RUNOUT
③	IWBRS 374. R.H. CHORDWISE SPLICE PANEL TAB UPPER SURFACE
④	W.S. 77. - CHORDWISE SPLICE - R.H. UPPER SURFACE SPLICE PLATE

Fig. 6 C-141 DADTA quality assessment—analytical back-tracking summary.

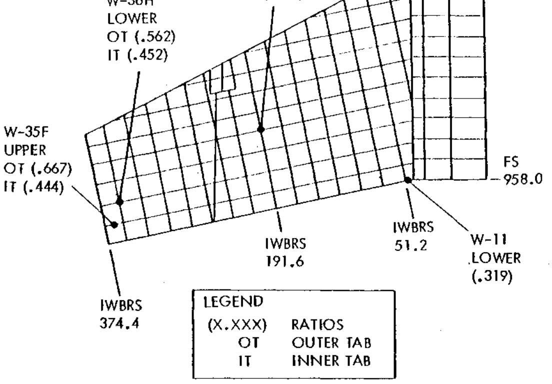


Fig. 7 C-141A DADTA summary of C-141A force-to-test ratios.

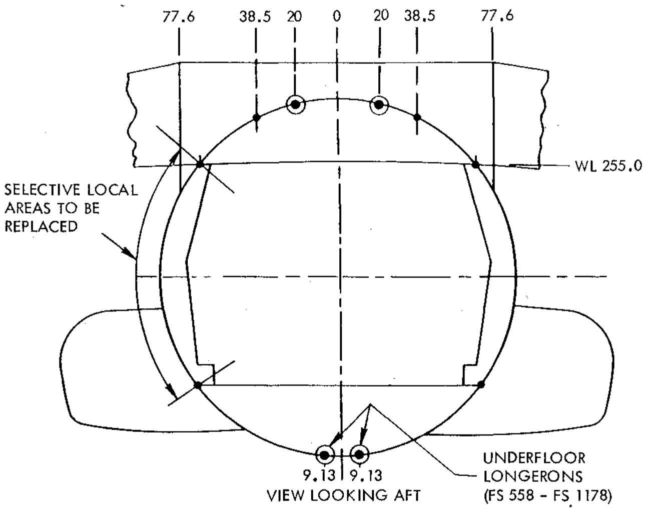


Fig. 8 Upper longeron beef-up and midfuselage skin beef-up.

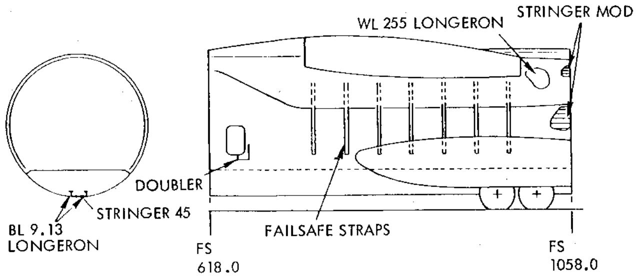


Fig. 9 Center fuselage modification.

beefing up two of the four upper longerons that go through the center-wing box and reskinning the side panels between the two fuselage-wing stick frames. These changes would have presented several problems.

1) Some center-wing planks would have to be removed to provide necessary access.

2) Removal of the side panels would complicate the jacking operations necessary to place the aircraft in the "jig" or "zero load" position.

3) Significant engineering and rework would be needed inside the center-wing box.

4) A labyrinth of hydraulic lines attached to the side panels is subject to removal and reinstallation during reskinning, a difficult and expensive process.

In view of these expensive problems it became apparent that trade studies for other beef-up configurations were needed.

The major tool used for the trade studies was computerized finite-element analysis. The advanced techniques in substructures analysis (module coupling) developed during the C-5A and C-130 derivative programs made it possible to analyze large complex structures to provide interaction effects of interfacing structures such as the area under consideration. Several beef-up designs were modeled in an attempt to find a replacement for the baseline design that would eliminate the associated problems listed above. The results indicated that the additional fuselage vertical bending capability required for the lengthened fuselage could be provided entirely by two belly longerons, as shown in Fig. 9.

Additionally, except for the requirement for external failsafe straps, the entire fuselage side panels could be left intact, eliminating the removal and replacement of the hydraulic service centers.

Detail Design

The next task was to translate the above findings into a detail design which would introduce the required longerons in the belly structure.

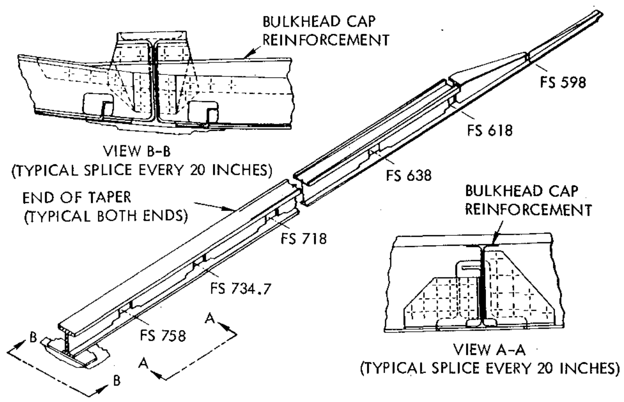


Fig. 10 New underbelly longeron.

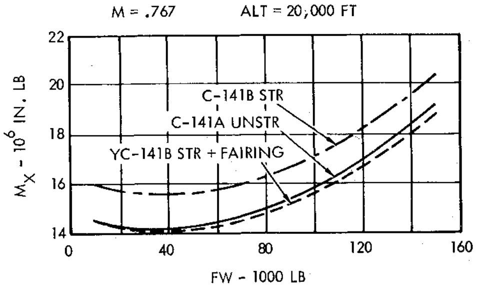


Fig. 11 Flight test measured 1.0*g* mean load.

After several design iterations, the project design organization with the support of peripheral structures technology disciplines converged on the longeron configuration shown in Fig. 10.

The cross section shown in view B-B is essentially an I-beam, to provide stability against buckling. The axial load-carrying components are the external strap and the inner cap, both of which are continuous. The inner cap is placed above the underfloor bulkhead caps to avoid interference. At each bulkhead location, the I-beam extrusion, of which the inner cap is a part, is notched to clear the bulkhead caps.

The resulting installation is relatively simple. After fuselage demate, the I-beam extrusion is threaded from one end. The outside strap is then positioned and the whole assembly fastened together with two existing stringers, as shown in view B-B. The design approach keeps intact the fuselage bulkhead caps at all locations. Lateral stability of the inner cap is provided by the shear ties shown in view B-B. The forward and aft portions of the longeron are tapered to affect a smooth and gradual load buildup.

Flight Test Results

An air load survey was conducted on the aircraft prior to modification and after modification. This procedure had the virtue of eliminating speculation about the quality of old flight test data which might be biased by the aircraft, the flying technique, or instrumentation differences. Test results are shown in Fig. 11. The test data verified the analytical values.

C-141B Proof Load Testing

The C-141B fuselage successfully withstood limit applied loads for 2*g* taxi and 2.5*g* maneuver load conditions, which produce maximum shear loads and bending loads, respectively. Approximately 300 strain gages and 30 deflection gages were used to measure structural response. Correlation between predicted and measured stresses was good. Ultimate strength was verified by extrapolating measured limit stresses to ultimate values.

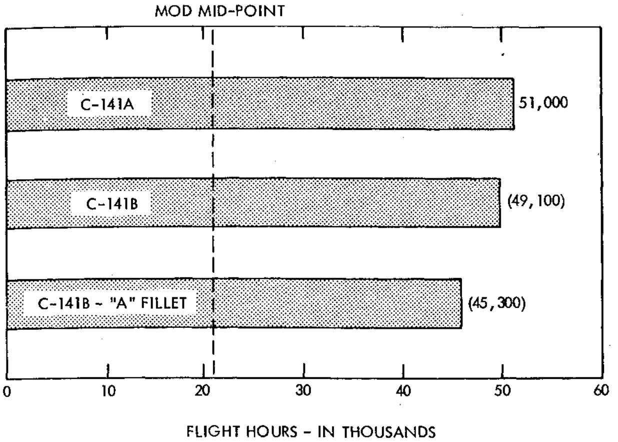


Fig. 12 C-141 wing fillet study durability analysis.

Table 2 Summary

Cost considerations	Flyaway cost
Conception:	
90 new C-141A's	$1,400,000,000
23.3-ft fuselage stretch mod	$332,000,000
Proposal:	
Added aerial refueling	$372,000,000
Full-scale development:	
Design layout phase	$362,595,475
Change from 275 A/C to 271 A/C and develop detail design	$322,637,966
Eliminating new fairing and relocate forward plug	$243,888,889
Production:	
Design refinements and manufacturing improvements for rate	$243,757,183

Project Estimate Projection (Design to Cost)

A value engineering design-to-cost (DTC) program tracked the cost during the prototype development and early production phases of the program.

Excluding some test and other nonrecurring costs, the full-scale development program started with a unit cost of $1,368,600 for 275 aircraft or a total of $376,365,000. Decisions were made to use the same materials, fasteners, processes, and construction techniques; retain the same type fuel, hydraulic, oxygen, controls, electrical lines, and fittings; use some in stock values and switches; and use the same support equipment (SE) and maintenance procedures. Such decisions limited the impact on procurement and handbooks resulting in early identified savings to bring the "design-to-cost" goal to $362,595,475.

During detail design, 188 trade studies were conducted with 379 DTC studies, identifying decisions that lowered the cost to $322,637,966. The largest savings were associated with the decision to change the midfuselage beef-up from side panels and upper longerons to installation of underbelly longerons. This change resulted in a simpler jacking procedure, less tooling, lower labor and material costs, and a weight savings of 330 lb, projecting a savings of $21,534,974. Most of the savings were much smaller, on the order of $50,000.

Production

It became apparent as the work proceeded that a slight change in the location of the forward plug mating splice, while requiring some redesign, would result in significant simplification of the manufacturing tasks. The forward mate joint was moved from FS 734.7 (at the front spar) to FS 618. This removed the requirement to disturb the forward wing fairing and all the systems that are attached to the front spar.

Retain the "A" Fillet

If you examine the durability results from the DADTA, such as in Fig. 12, it is apparent that the fillet very nearly achieves the desired result of not reducing the service life of the C-141A aircraft. Both values are well in excess of the 40,000 hour USAF "goal" current for the aircraft in 1975. It appeared to the USAF that a tradeoff was possible that would be cost effective; viz., retain the C-141A fillet. The same situation existed in the performance data. While the new fillet improved performance, the amount was not enough to make a significant life-cycle cost improvement. Cycling the whole process again to refair the fillet to improve drag and "tailor" the durability to 40,000 hour was deemed too risky on a concurrent basis and too late and expensive on a "fly before you buy" basis. A decision to accept the degradation in life and go without the fillet was made, thus saving $126,910,000.

Final Design Effort

With an extensive effort over a four-year period, the program could proceed. Some additional time delay was required to provide engineering for the relocated fuselage break and accommodate the original "A" aircraft fillet.

We believe Lockheed and the USAF are satisfied that all major cost drivers were identified and addressed. The design/produce-to-cost activity functioned up through achieving production rate to assure implementation of numerous decisions and to provide tradeoff data for resolution of some problem reports and discrepancies.

Conclusions

The economic life estimates continued to be confirmed, as the full-scale fatigue test article has successfully reached 118,000 CTH, of which 90,000 test hours were block loads and 28,000 test hours were a flight-by-flight sequence of loads.

As shown in the summary, Table 2, the flyaway cost varied from $1,400,000,000 in the conception phase for 90 new C-141A's to $243,757,183 in the production phase for a 30% increase in cargo volume and added aerial refueling on 271 C-141B's. This large reduction in cost was a result of the in-depth value engineering trade studies and innovative application of structures and design technology, resulting in synergistic savings in cost and weight.

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