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DAMAGE TOLERANCE AND LOGISTIC TRANSPORT DESIGN

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DAMAGE TOLERANCE IN AIRLIFTER DESIGN

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INTRODUCTION

Efficient and safe operation of the complex air transports of today and the increasing complexity of designs proposed or in production for use in the 1970's emphasizes problems of reliability, maintainability and operational safety. One approach to enhancing these characteristics of airlifters, adopted and used by the Lockheed-Georgia Company, is damage tolerance design.

Damage tolerance relates to the capability of an aircraft structure to sustain a limited amount of damage without endangering safe operation. To do this the structure must retain the capability of supporting a reasonable percentage of design load after being damaged. Complete failure of a structural member is permissible within the scope of this definition, provided alternate structures or systems exist which allow continued safe operation of the aircraft.

Some 20 years ago, the terms "Fail Safe" and "Safe Life" were coined to focus attention of aeronautical and structural engineers on the importance of recognizing safety-related problems affecting structures as a consequence of extended-time operation of passenger aircraft. "Fail Safe" and "Safe Life" designs attempted to account for fatigue considerations; that non-fatigue related damage could and would occur; and that monocoque construction, with its inherent structural redundancies, offered protection against many types of localized damage.

No standard solution exists to resolve the problem of structural safety. Diverse opinions within the aerospace industry have led to a number of approaches in structural design and test. Some companies relied on fatigue resistance concepts or on a minimum safe life design as the only attainable solution. Others leaned towards a "Fail Safe" approach. In general, American civil aircraft manufacturers favored structural redundance, coupled with fatigue resistance designs. This choice held economic implications in that it was hoped to reduce the necessity for painstaking fatigue tests for a complete aircraft. In time, this approach was modified so that today practically all producers of civil transport aircraft incorporate structural redundancy and submit the basic structure to complete fatigue or repeated load tests backed by service life warranties.

Although damage tolerance design has not been universally accepted, operational experience with military and commercial airlifters tends to substantiate the need for such an approach to supplement conventional repeated load or fatigue resistance design techniques. Most engineers believe that some degree of damage tolerance is desirable in design, but few rank it in importance with fatigue resistance or static strength considerations. While not advocating damage tolerance as a substitute for fatigue resistance, Lockheed-Georgia favors requiring damage tolerance design in all manned aircraft, especially in military and commercial logistic transports.

THE CASE FOR DAMAGE TOLERANCE DESIGN

Present utilization rates of military logistic transports parallel, and often exceed, that achieved in commercial airline operations. This situation, and the need for inherently high reliability in military airlifters to operate effectively under conditions of rapid accumulation of service time and adverse environments, has led Lockheed-Georgia to incorporate damage tolerance concepts into structural designs.

Lockheed-Georgia produces the C-130 Hercules, the C-140 JetStar, the C-141 StarLifter, and the massive C-5 Galaxy. These aircraft are pictured in Figures 1 through 4, respectively.

Fig. 1 - C-130 Hercules

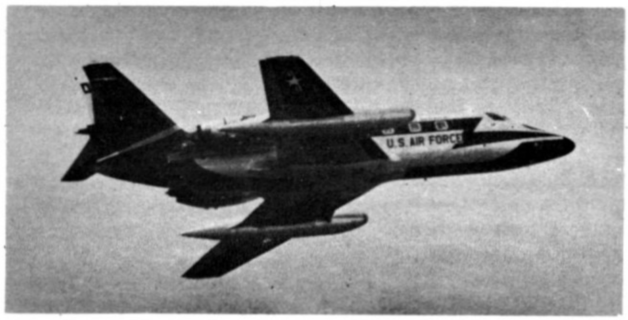


Fig. 2 - C-140 JetStar

Fig. 3 - C-141 StarLifter

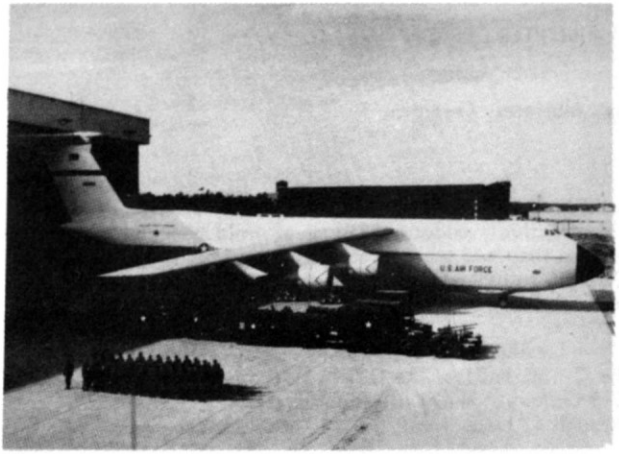


Fig. 4 - C-5 Galaxy

The U. S. Air Force Military Airlift Command is the predominant user of the C-141 and will be for the C-5 when it is placed in operational service. In various configurations, the C-130 is employed in all branches of the U. S. Military establishment except the U. S. Army; by several other nations; and with commercial airlines as an air-freighter. The commercial Hercules is designated as the Lockheed-100 and in a new, stretched configuration, as the Lockheed 100-20. The C-140 is in service with the U. S. Presidential fleet, the U. S. Air Force, and more than 100 business corporations.

Using the C-141 as an example, the average daily utilization rate of this airlifter exceeded eight hours throughout the month of February 1968. One C-141, based at Dover AFB, Delaware, achieved an average daily utilization rate of 21-1/4 hours in March 1968.

This type of operation differs greatly than that conceived at the time of initial design. Such high utilization rates, coupled with the extremely severe environments in military operations, can accelerate damage due to corrosion, fatigue, and overloads.

With more than ten years of operational experience, the C-130 has proven to be an excellent testbed for damage tolerance design. Although losses of C-130 aircraft have occurred from various causes, none have been attributed to fatigue, corrosion, or related effects. Examples of damage sustained by C-130's and other Lockheed-Georgia aircraft will serve to illustrate the value of damage tolerance design.

An improperly locked door, suddenly opened in flight at 20,000 feet altitude, caused explosive decompression and the damage pictured in Figure 5. The C-130, however, recovered and landed safely.

Fig. 5 - C-130 Explosive Decompression Damage

Corrosion damage to a C-130 pressure shell and structural bulkhead, caused by a leaking latrine is shown in Figure 6. Another example of corrosion damage is pictured in Figure 7. Here, corrosion attacked a lower wing plank affecting several integral panels. This was caused by water entrapment between a titanium heat shield and the wing plank structure.

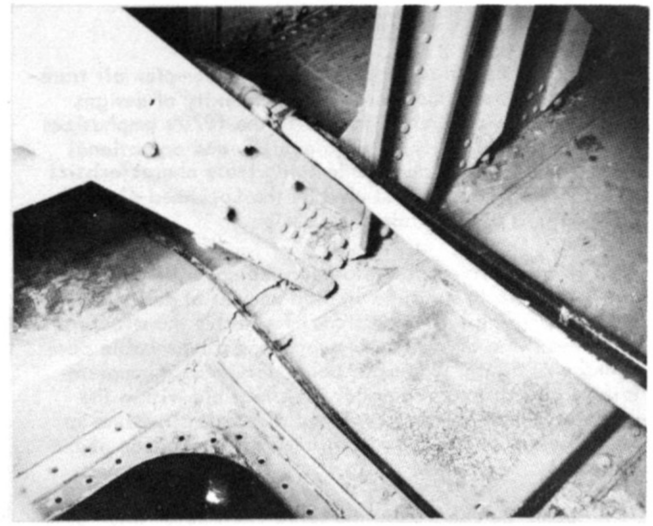


Fig. 6 - C-130 Corrosion Damage

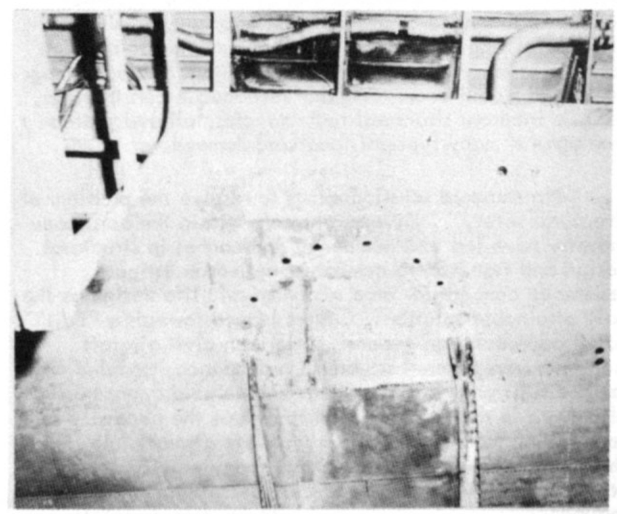


Fig. 7 - C-130 Corrosion Damage

Repeated ground and pressure loads initiated the dangerous crack shown in Figure 8. Laboratory analysis of the C-130 structure indicated that sufficient strength remained to provide an adequate margin of operational safety.

An unexpected dive maneuver in a C-140 resulted in the damage to the horizontal tail structure pictured in Figure 9. Here again, the aircraft recovered and landed safely.

Examples of C-130 battle damage contained by damage tolerance design are shown in Figures 10 and 11. In Figure 10, the damage to an integrally machined plank spans several risers. No progression of the fracture is evident.

Damage sustained by pressure skins, frames, and fixed and movable control surfaces is illustrated in Figure

11. As in the previous case, no progression of the damage is evident. Both of the C-130's survived these incidents.

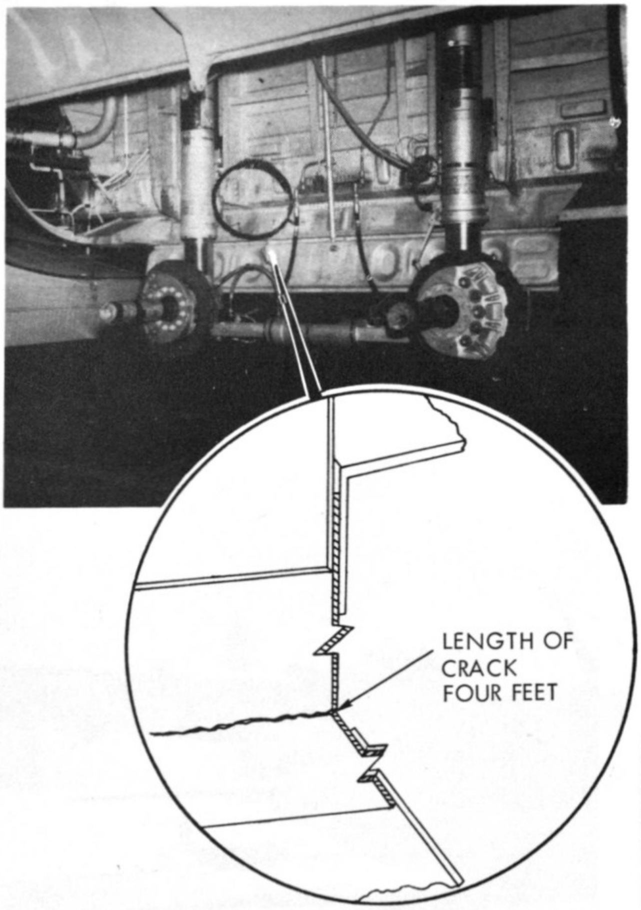


Fig. 8 - C-130 Chine Crack Damage

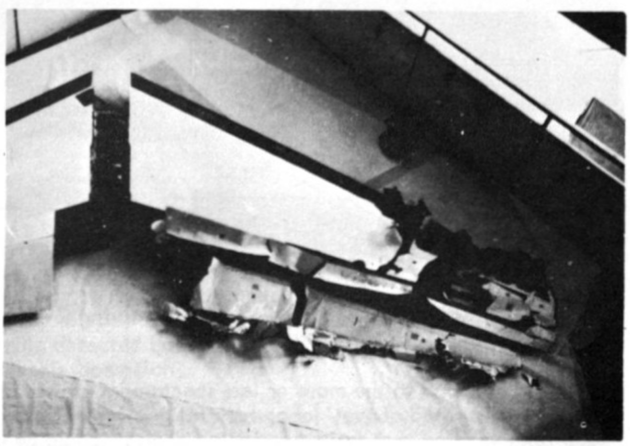


Fig. 9 - C-140 Horizontal Stabilizer Damage

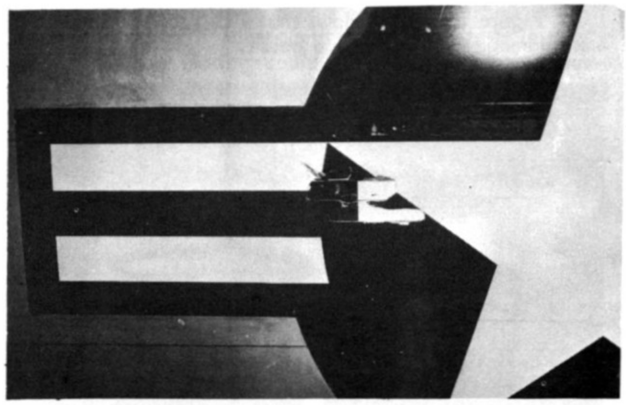


Fig. 10 - C-130 Battle Damage

Fig. 11 - C-130 Battle Damage

Other examples of non-fatigue related damage are pictured in Figure 12 through 17. In all cases, damage was sustained without catastrophic failure of the aircraft structure.

A bird nest, similar to that shown in Figure 12, was suspected as the cause of an in-flight C-130 fire that resulted in considerable structural damage.

Fig. 12 - Suspected Cause of C-130 In-Flight Fire

Figure 13 simply shows that a C-130 is somewhat more damage tolerant than a goose.

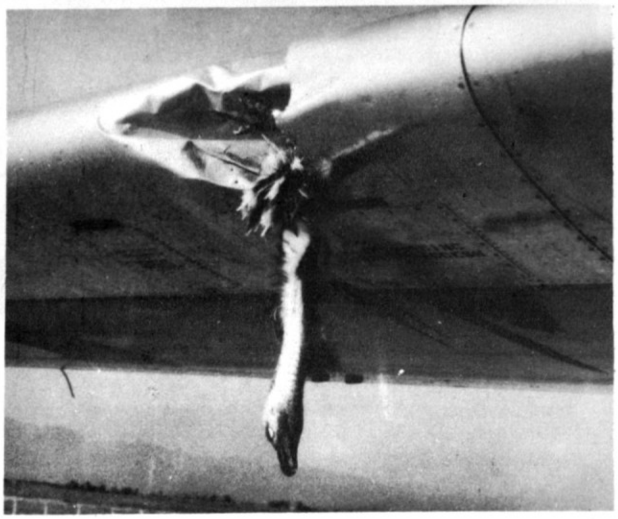


Fig. 13 - C-130 Wing Damage

In Figure 14, the consequences of striking a horse that wandered onto the runway during landing of a C-141 is pictured. In this case, the damage propagated to some degree during the flight to a repair base.

Fig. 14 - C-141 Main Landing Gear Fairing Damage

A landing gear door, separating in flight, struck the horizontal stabilizer of a C-130, as shown in Figure 15. The door separated as a consequence of exceeding design speed in an inadvertent dive.

Loss of a propeller in flight caused the damage to a C-130 pictured in Figure 16.

The C-140 damage indicated in Figure 17 was the result of an in-flight collision.

While all the circumstances leading to these effects could hardly be accounted for, anticipation of possible in-service damage prompted damage tolerance design in C-130, C-140, and C-141 structures. The same degree of damage tolerance is provided in the giant C-5 structure.

Fig. 15 - C-130 Horizontal Stabilizer Damage

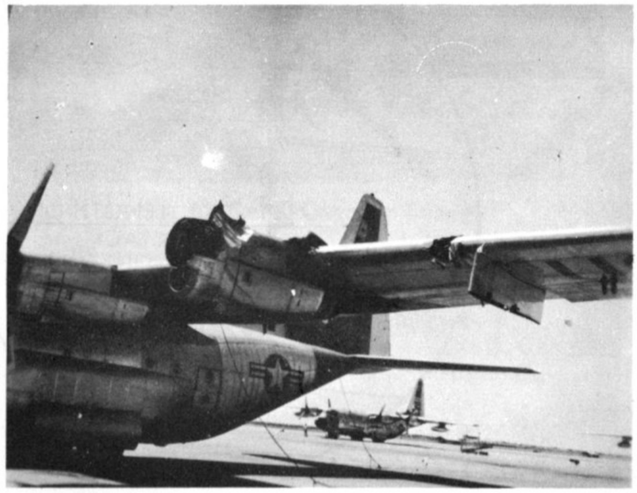


Fig. 16 - Result of Propeller Loss on C-130

Fig. 17 - Result of In-Flight Collision Involving C-140

In addition to the more or less spectacular causes of damage illustrated above, laboratory fatigue inspections and tests verified that fatigue-oriented damage could be anticipated much sooner than normal operational records would indicate when aircraft were subjected to extremely high utilization and severe operating environments. Figures 18 and 19 picture fatigue cracks measuring twenty and eight inches in length, respectively. These cracks were induced by laboratory fatigue tests on wing structures. Similar cracks have developed on in-service C-130 aircraft as a consequence of hard use. The laboratory tests, simulating the severe operating environment, led to inspection schedules to detect these cracks as early as possible. Damage tolerance design greatly lessened the possibility of such cracks causing a serious accident or requiring excessive down time for emergency repair. Cracks such as these were contained sufficiently by damage tolerance design to permit safe operation until the using command was able to ferry the aircraft to a repair base at their convenience.

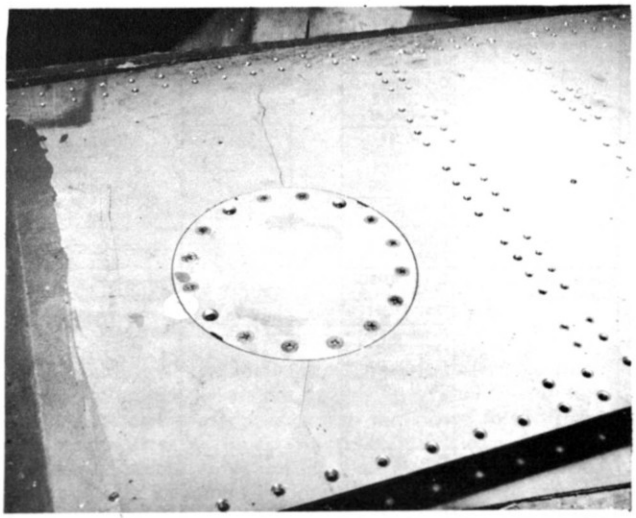


Fig. 18 - C-141 Fatigue Crack

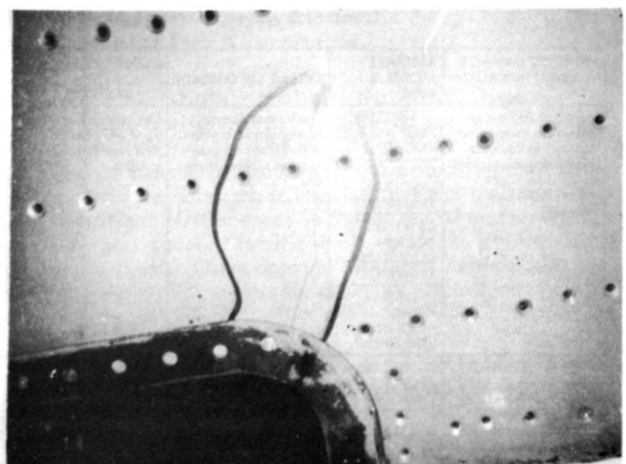


Fig. 19 - C-130 Fatigue Crack

Under conditions of severe usage, damage can develop and propagate with unexpected rapidity. A damage tolerant structure, however, greatly increases the chances of damage being detected before it reaches critical proportions affecting safe operation.

To some extent, damage tolerance design is forgiving of human error. Sometimes, in fabrication, or during overhaul or repair operations, a part has been omitted or incorrectly installed. Subsequent acceptance tests involving pressurization or loading could have resulted in a serious accident had not the structure been designed to be damage tolerant. As embarrassing as these incidents are, they serve to substantiate the value of damage tolerance design.

DAMAGE TOLERANCE LEVELS IN DESIGN

It is difficult, and in some instances impossible, to ascertain all possible types and sources of in-service damage to aircraft. Consequently, it is often just as perplexing to specify how damage tolerant a structure should be. Damage tolerance levels must always conform to existing and accepted design standards, such as "Fail Safe" requirements, and even improve upon them.

Accordingly, at Lockheed-Georgia, damage tolerance minimum requirements meet or exceed the U. S. Federal Aviation Regulation, Part 25, relating to Airworthiness Standards for Transport Category Airplanes.

At present, all C-130, C-140, and C-141 designs have been certificated as meeting these civil requirements in addition to military design requirements spelled out in various specifications. A design objective for the C-5 is to have it certificated also. In general, all of these requirements have been met with positive safety margins. This means that, in many instances, the structures involved have a greater damage tolerance than called for in the regulations. An important fallout of this philosophy is that in providing for damage tolerance capabilities meeting required load levels, even more protection is afforded in containing damage at lower load levels.

Tables 1 through 6 indicate how damage tolerance criteria are applied to Lockheed-Georgia designs. These tables delineate the extent of structural damage which can be tolerated in particular structures. Here, a type of damage is assumed and its extent is related to various aircraft. Then an ultimate load capability for the structure is established to serve as damage tolerance design criteria.

Table 1
Fuselage Pressure Cabin

TYPE OF DAMAGE ASSUMED IN DESIGN	AIRCRAFT MODEL & TYPE	EXTENT OF DAMAGE	ULTIMATE LOAD CAPABILITY OF DAMAGED STRUCTURE
Longitudinal Crack in Pressure Cabin	C-130 TURBO-PROP ASSAULT TRANSPORT	Circumferential ring failed, accompanied by skin crack across both adjacent skin panels.	2.0g maneuver or 49 fps gust encounter with full cabin operating pressure.
	C-140 JET EXECUTIVE TRANSPORT	Circumferential ring failed, accompanied by 12 inch long skin crack.	
	C-141 JET MEDIUM LOGISTICS TRANSPORT	Same as C-140	
	C-5A JET HEAVY LOGISTICS TRANSPORT	Circumferential ring failed, accompanied by skin crack across both adjacent skin panels.	
Circumferential Crack in Pressure Cabin	C-130 TURBO PROP ASSAULT TRANSPORT	Longeron failed, accompanied by 36 inch long skin crack	2.0g maneuver or 49 fps gust encounter with full cabin operating pressure differential.
	C-140 JET EXECUTIVE TRANSPORT	Longeron failed, accompanied by 12 inch long skin crack.	
	C-141 JET MEDIUM LOGISTICS TRANSPORT	Any single longitudinal stringer failed, plus skin crack across both adjacent skin panels.	
	C-5A JET HEAVY LOGISTICS TRANSPORT		

Table 2
Wing Box Structure

TYPE OF DAMAGE ASSUMED IN DESIGN	AIRCRAFT MODEL & TYPE	EXTENT OF DAMAGE	ULTIMATE LOAD CAPABILITY OF DAMAGED STRUCTURE
Chordwise crack in box upper or lower surface skin.	C-130 TURBO PROP ASSAULT TRANSPORT		
	C-140 JET EXECUTIVE TRANSPORT	One spanwise skin plank fully cracked.	2.0g maneuver or 49 fps gust encounter.
	C-141 JET MEDIUM LOGISTICS TRANSPORT		
	C-5A JET HEAVY LOGISTICS TRANSPORT		
Vertical crack in box front or rear spar web.	C-130 TURBO-PROP ASSAULT TRANSPORT		
	C-140 JET EXECUTIVE TRANSPORT	Web crack extending from upper cap to lower cap.	2.0g maneuver or 49 fps gust encounter.
	C-141 JET MEDIUM LOGISTICS TRANSPORT		
	C-5A JET HEAVY LOGISTICS TRANSPORT		

By placing emphasis on the type of damage that can be sustained, rather than on a speculative cause of damage, a more positive and rational approach is realized in evolving damage tolerance criteria. Data may also be related to damage or failures occurring in actual operation to validate assumed design damage.

Table 3
Horizontal and Vertical Stabilizer Box Structure

TYPE OF DAMAGE ASSUMED IN DESIGN	AIRCRAFT MODEL & TYPE	EXTENT OF DAMAGE	ULTIMATE LOAD CAPABILITY OF DAMAGED STRUCTURE
Chordwise crack in box upper or lower surface skin.	C-130 TURBO-PROP ASSAULT TRANSPORT	Any single stringer or skin panel fully cracked.	
	C-140 JET EXECUTIVE TRANSPORT		2.0g maneuver or 49 fps gust encounter
	C-141 JET MEDIUM LOGISTICS TRANSPORT		
	C-5A JET HEAVY LOGISTICS TRANSPORT	One spanwise plank fully cracked.	
Vertical crack in box front or rear spar web	C-130 TURBO-PROP ASSAULT TRANSPORT		
	C-140 JET EXECUTIVE TRANSPORT	Web crack extending from upper cap to lower cap.	2.0g maneuver or 49 fps gust encounter.
	C-141 JET MEDIUM LOGISTICS TRANSPORT		
	C-5A JET HEAVY LOGISTICS TRANSPORT		

Table 4
Control Surfaces

TYPE OF DAMAGE ASSUMED IN DESIGN	AIRCRAFT MODEL & TYPE	EXTENT OF DAMAGE	CONSEQUENCES OF DAMAGE
Loss of one complete aileron	C-130 TURBO-PROP ASSAULT TRANSPORT	Surface separates cleanly, not inflicting structural damage beyond immediate supports on parent structure.	Roll response is impaired, but mission accomplishment is feasible.
	C-140 JET EXECUTIVE TRANSPORT		
	C-141 JET MEDIUM LOGISTICS TRANSPORT		
	C-5A JET HEAVY LOGISTICS TRANSPORT		
Loss of one complete elevator or segment	C-130 TURBO-PROP ASSAULT TRANSPORT		Pitch response is impaired but mission accomplishment is feasible.
	C-140 JET EXECUTIVE TRANSPORT		
	C-141 JET MEDIUM LOGISTICS TRANSPORT		
	C-5A JET HEAVY LOGISTICS TRANSPORT		
Loss of rudder or rudder segment	C-130 TURBO-PROP ASSAULT TRANSPORT		Yaw control is impaired but mission accomplishment is feasible.
	C-140 JET EXECUTIVE TRANSPORT		
	C-141 JET MEDIUM LOGISTICS TRANSPORT		
	C-5A JET HEAVY LOGISTICS TRANSPORT		

Table 5
Control Systems

TYPE OF DAMAGE ASSUMED IN DESIGN	AIRCRAFT MODEL & TYPE	EXTENT OF DAMAGE	CONSEQUENCES OF DAMAGE
Structural failure of any single component involved in transmission of manual control action from flight station to surface affected.	C-130 TURBO-PROP ASSAULT TRANSPORT	Fracture or jamming of any single bracket, pulley, cable, pushrod, or support thereof.	Use of duplicate system by unaffected pilot permits safe completion of mission.
	C-140 JET EXECUTIVE TRANSPORT		
	C-141 JET MEDIUM LOGISTICS TRANSPORT		
	C-5A JET HEAVY LOGISTICS TRANSPORT		
Structural failure or loss of hydraulic or electric power to any single power unit utilized in operation of control surfaces.	C-130 TURBO-PROP ASSAULT TRANSPORT	Component fracture, jamming, hydraulic line rupture, or severance of electrical power for any control surface power unit.	Duplicate power units, hydraulic systems and electrical circuits permit safe continuation of mission.
	C-140 JET EXECUTIVE TRANSPORT		
	C-141 JET MEDIUM LOGISTICS TRANSPORT		
	C-5A JET HEAVY LOGISTICS TRANSPORT		

Table 6
Auxiliary Control Devices

TYPE OF DAMAGE ASSUMED IN DESIGN	AIRCRAFT MODEL & TYPE	EXTENT OF DAMAGE	ULTIMATE LOAD CAPABILITY OF DAMAGED STRUCTURE
Loss of any single wing trailing edge flap segment	C-130 TURBO-PROP ASSAULT TRANSPORT	Surface separates cleanly, not inflicting structural damage beyond immediate supports on parent structure.	Unsymmetrical flight characteristics may be corrected by use of ailerons. Continuation of landing or takeoff operation at degraded field length minimums is feasible.
	C-140 JET EXECUTIVE TRANSPORT		
	C-141 JET MEDIUM LOGISTICS TRANSPORT		
	C-5A JET HEAVY LOGISTICS TRANSPORT		
Loss or malfunction of any single wing spoiler segment	C-141 JET MEDIUM LOGISTICS TRANSPORT		
	C-5A JET HEAVY LOGISTICS TRANSPORT		
Loss or malfunction of any single wing leading edge slat segment	C-5A JET HEAVY LOGISTICS TRANSPORT		

DAMAGE TOLERANCE ANALYTICAL AND TEST METHODS

Analytical and test methods used to determine that desired tolerance levels are actually provided in structural designs are essentially the same as those used to confirm static strength provisions. Since analysis is empirical in nature and based on test results, few new tests are needed except where structural designs differ significantly from types already tested. Furthermore, since analysis relates to tests where damage is simulated while the structure is undergoing damage tolerance design loads, no multiplying factors accounting for dynamic effects of failure under load are necessary. Here, as in static design tests, a margin of safety of zero is permissible.

Prior to initiating analysis, the extent, type of damage, and load levels to be achieved are specified as outlined in Tables 1 through 6. These basic criteria are designed to ensure that damage may be readily detectable before structural strength is impaired beyond the point of safe operation. Differences in design detail among various aircraft types account for the small variances in criteria applied to them. Once damage tolerance criteria are defined, the structure may be designed to conform accordingly.

A rather simple concept serves as the basis of determining ultimate strength of a damaged fuselage skin panel. This concept makes use of a fictitious effective width, W_e, measured ahead of the tips of a crack in the skin, as shown in Figure 20. Figure 21 illustrates variations of W_e as a function of material types and crack lengths as determined from tests. Any residual strength analysis of damaged panels must account for significant variations in other parameters affecting W_e such as panel geometry, type and rate of loading, temperature, and sheet thickness. Provided the ranges of important parameters or combinations are not exceeded, good agreement is realized between predicted stresses and measured stresses.

The approach to determining damage tolerant residual strength considers natural crack stoppers such as stringers and skin splices located perpendicular to the longitudinal axis of the crack. Several typical cracks which may be considered are outlined in Table 7. Table 7 is used in conjunction with Figures 21 and 22 to predict, in a straightforward manner, the residual strength of the damaged panel. Predicted strength is then compared with required strength to determine the existing level of damage tolerance.

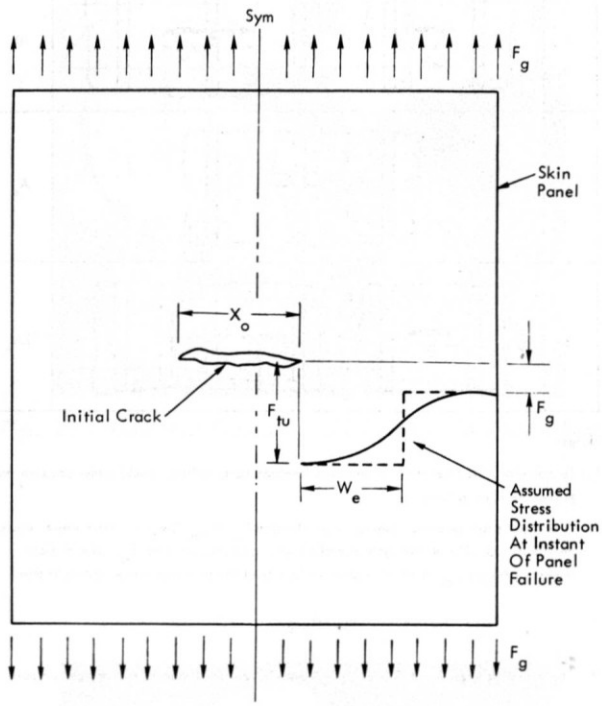


Fig. 20 - Skin Panel Damage Analysis

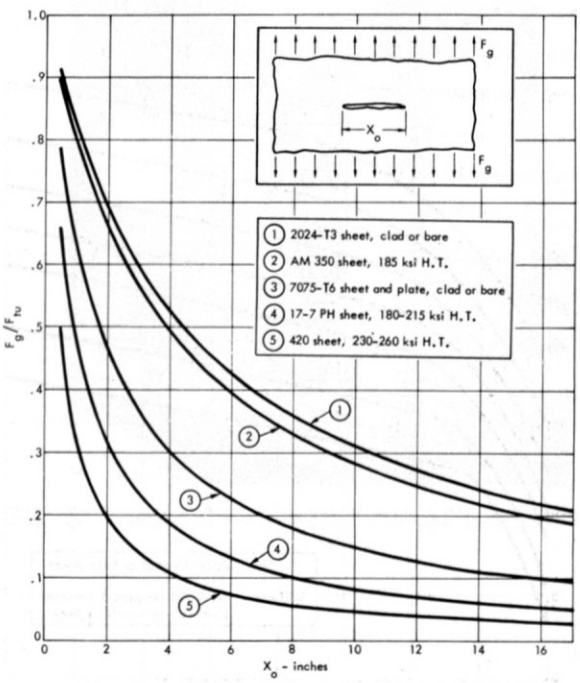
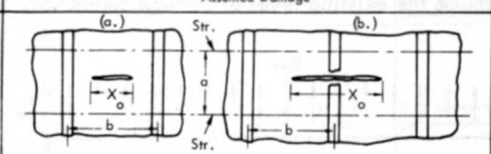
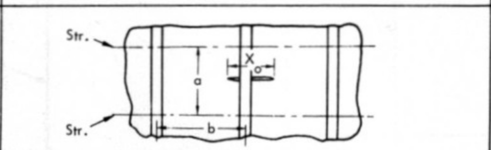
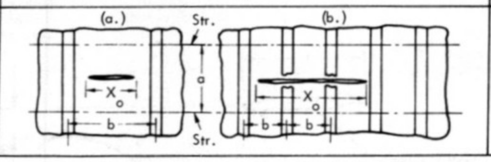


Fig. 21 - Tear Strength of Flat Sheet With a Crack Perpendicular to Tension Load (Infinite Sheet Width)

Table 7
Curved, Stiffened Panels With Longitudinal Crack
Under Internal Pressure

Case	Assumed Damage	ΣA_e
1		0
2		A_e
3		$2A_e$

Notes:

1. To calculate the strength of a damaged fuselage (longitudinal crack) under pressure the procedure is as follows:

   First assume the extent of damage and calculate $F_{tuf}/F_{tus} \cdot \Sigma A_e/t$. With these values, determine from Fig. 4 through 6 the allowable hoop tension stress F_g. The critical internal pressure p_{cr} at which explosive failure of the skin and frames occurs is then

$$p_{cr} = F_g \frac{t}{R}$$

2. The effective area A_e of] - or [- frames is very small due to the stringer cutouts

$$A_e \cong \frac{1}{5} A_f$$

   It increases to $A_e \cong \frac{1}{3} A_f$ if a reinforcing angle is attached to the frame close to the stringer cutout. For a strap attached to the cracked skin A_e is the full area of the strap, $A_e = A_{strap}$.

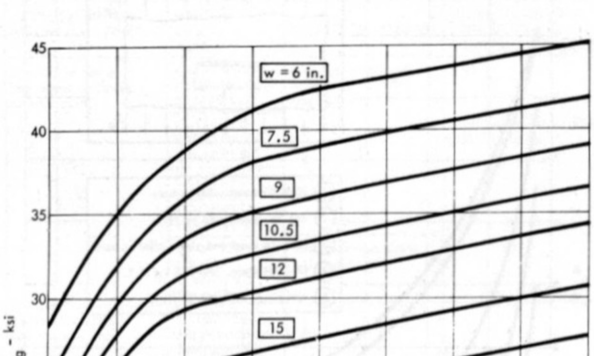


Fig. 22 - Ultimate Strength of Flat, Stiffened Panels and Slightly Curved Panels With Circumferential Crack

A multi-element concept is employed to achieve damage tolerance on a wing surface. Here, the wing cover is fabricated mechanically attaching several extruded planks together in a spanwise direction. Particular care is taken to ensure that each spanwise splice is able to arrest propagation of damage and that attachments are strong enough to transfer load from the damaged panel to adjacent structure without causing further failures. Lockheed-Georgia requires that all such attachments be designed to fail in bearing. This provides a soft joint which can deform and transfer the required load without producing high local stress concentrations. Component tests are conducted early in the design phase on critical regions of wing covers to verify that desired damage tolerance levels are achieved.

Cracking of a spar web is another typical wing damage mode that may be treated analytically. Damage tolerance is achieved by ascertaining that unfailed wing structure is capable of redistributing the damaged spar web load without causing propagation of the damage. Shear is redistributed by portal action of the spar caps and the crowns of adjacent upper and lower wing panels. If two or more spars are initially incorporated into wing design, damage tolerance is obtained by good detail design and without incurring any weight penalty.

Figures 23 through 27 illustrate tests conducted to verify analytical procedures and determine if desired damage tolerance levels have actually been achieved in design. Figure 23 shows a C-130 pressure shell that attests to the inadequacy of damage tolerance capabilities of an early design.

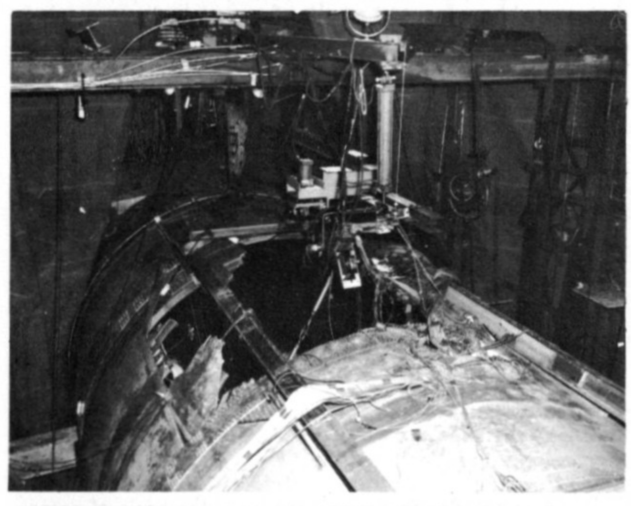


Fig. 23 - Results of Early C-130 Pressure Shell Test

A damaged spar web under limit load is depicted in Figure 24.

Figure 25 pictures results of damage tolerance tests on a C-141 pressure shell. Note how the damage was contained by the frame and titanium damage tolerance straps.

Figures 26 and 27 show exterior and interior views of a pressure shell subjected to damage tolerance pressurization tests.

Implements used to generate damage in structures under test are pictured in Figures 28 and 29. The 6.0-inch and 24.0-inch spears, pictured in Figure 28, simulate impact damage when they are shot into and through fuselage skins, stringers, and rings. The rotary saw of Figure 29 is used to cut through fuselage skins and stringers to simulate fatigue cracks. In the tests described here, damage is imparted to structures while under load. These techniques evolved from the need to simulate the effects of propeller parts separating and piercing fuselage shells, or turbine blade failures where fragments pierced shells and wing structures, or growing fatigue cracks. In some instances, cracks have been generated in structures under relatively low level repeated loads until they reached required damage tolerance lengths. The load was then increased to the maximum required level or until failure occurred.

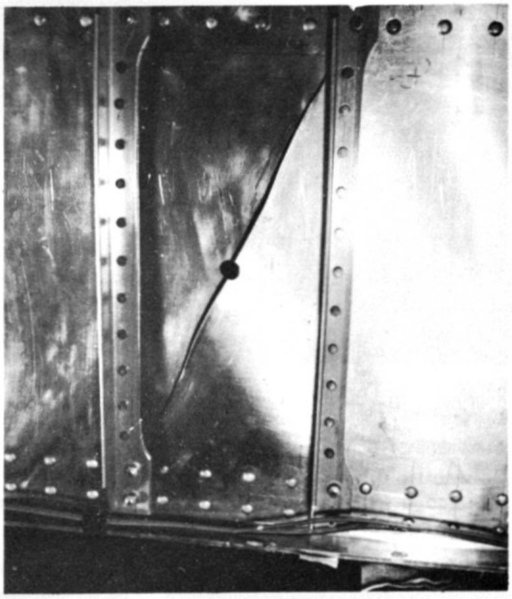


Fig. 24 - Damaged Spar Web

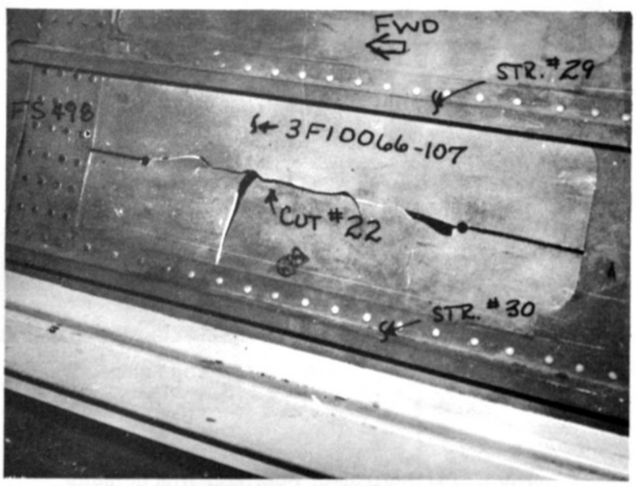


Fig. 25 - Results of C-141 Pressure Shell Test

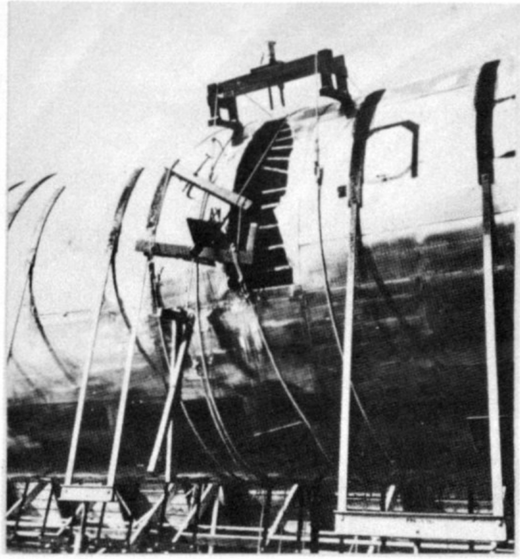


Fig. 26 - Results of Pressure Shell Damage Tolerance Test

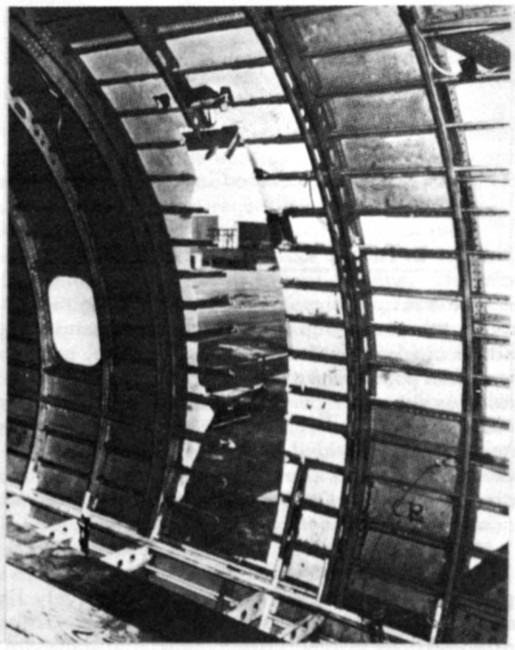


Fig. 27 - Results of Pressure Shell Damage Tolerance Test

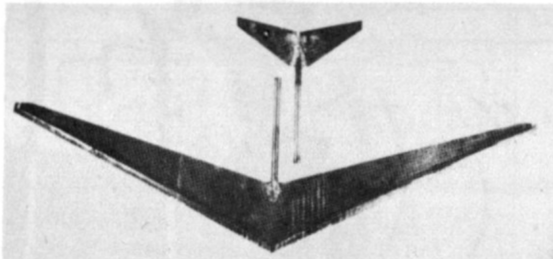


Fig. 28 - Damage Tolerance Test Spears

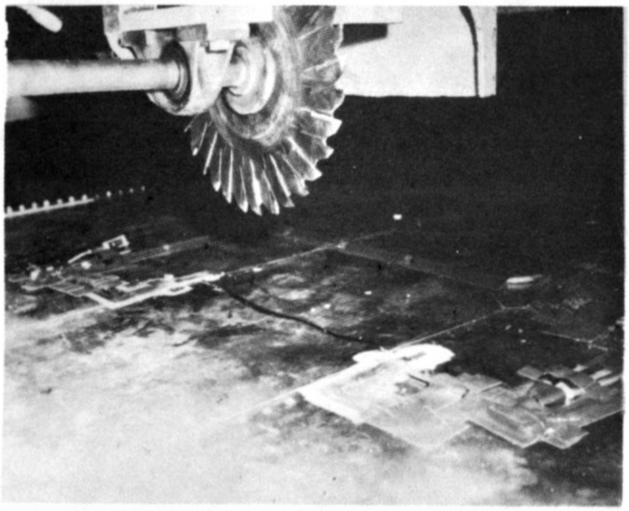


Fig. 29 - Rotary Saw Used in Damage Tolerance Tests

DAMAGE TOLERANCE STRUCTURE

Several practices are followed by engineers to derive damage tolerant structures. Lockheed-Georgia employs positive crack stoppers whenever practical, especially where skin panel dimensions or the dimensions of a structural segment under consideration materially exceed reasonable damage limits. Positive damage limiters or alternate paths are provided where the structure may be subjected to small arms fire. Crack stoppers or alternate load paths are mandatory where a material having a low resistance to crack propagation is used.

As mentioned previously, the use of joints with bearing critical fasteners is one method of positively limiting damage propagation. Where possible, shear critical or tension critical fasteners are avoided. If these are used, the joint involved is treated as being damaged and an alternate load path is provided in design.

In many cases, different materials are used in a structure to take advantage of differences in fatigue or static characteristics. Fail-safe titanium straps, for example, are extensively used in C-140, C-141 and C-5 structures as damage limiters in fuselage skins. These titanium straps, or damage limiters, and the skins they are bonded to are not likely to experience fatigue failures to the same degree at the same instant in time.

A C-130 outer wing structure is pictured in Figure 30. The spanwise joints of the four integrally machined wing planks are joined by bearing critical fasteners arranged in single rows.

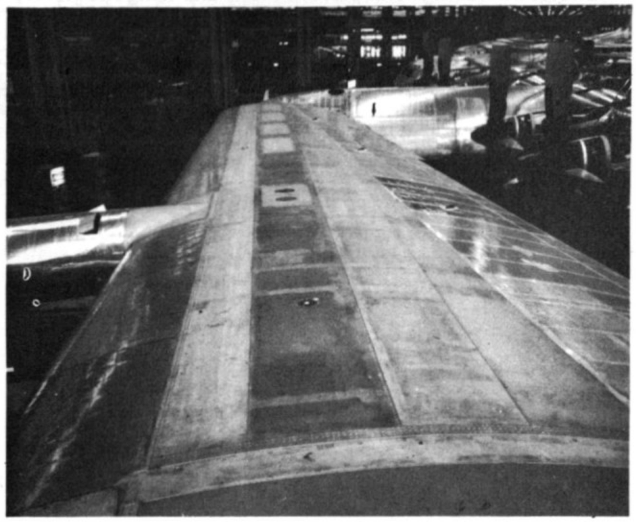


Fig. 30 - C-130 Outer Wing Structure

Multiple hooks and eyes with a latched tell-tale provide damage tolerance for the C-130 aft loading ramp shown in Figure 31.

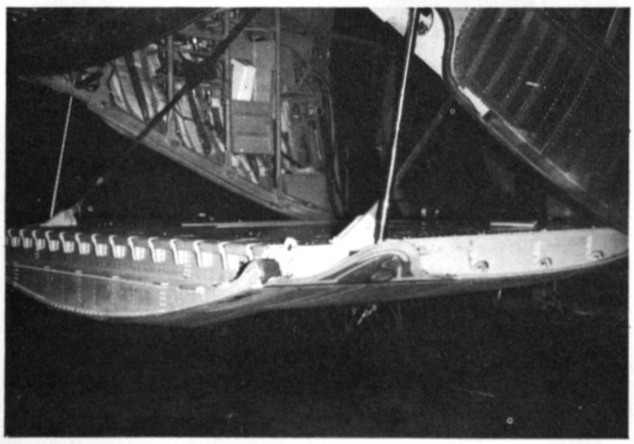


Fig. 31 - C-130 Aft Loading Ramp

The C-141 horizontal stabilizer trim actuator, sketched in Figure 32, features dual load paths as a damage tolerance feature.

Dual load paths are also provided in the design of the horizontal stabilizer pivot fitting for the C-5 shown in Figure 33.

Damage tolerance titanium straps are used extensively in the C-5 fuselage structure as evidenced in Figure 34. Note that damage tolerance straps are located under frame members, as well as mid-way between frames.

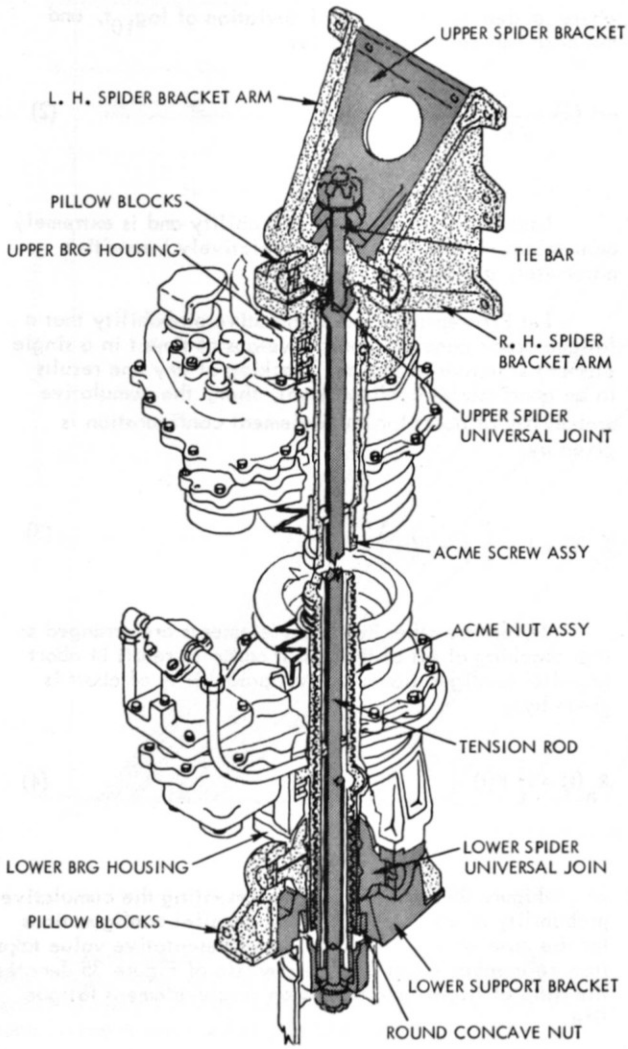


Fig. 32 - C-141 Horizontal Stabilizer Trim Actuator

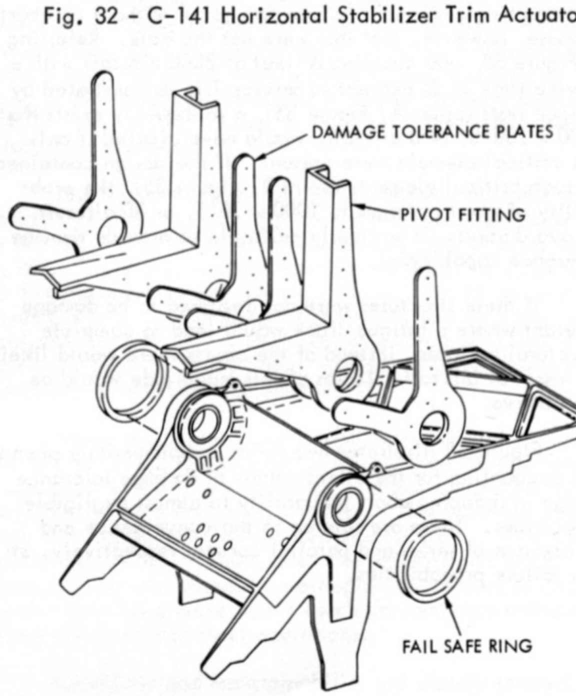


Fig. 33 - C-5 Horizontal Stabilizer Pivot Fitting

Fig. 34 - C-5 Fuselage - Damage Tolerance Straps

These examples provide some insight as to how damage tolerance concepts are applied to various structures. At Lockheed-Georgia, these concepts supplement, but never replace, fatigue resistance or repeated load requirements imposed on designs. No compromise of fatigue resistance requirements is ever entertained simply because a structure is considered to be damage tolerant. Furthermore, incorporation of damage tolerance design does not eliminate the need for structural inspections or the replacement of faulty or damaged components. Damage tolerance design is applied to enhance reliability, maintainability, and operational safety and actually assists in establishing orderly and effective inspection and maintenance schedules.

EFFECT ON AIRFRAME COSTS AND WEIGHT

In general, Lockheed-Georgia, after examining the question in depth, has found that cost and weight penalties incurred as a result of the application of damage tolerance design are so small as to be virtually unidentifiable. For example, it was proposed recently to substitute steel damage tolerance straps for the titanium straps used throughout the C-5. It was felt that the use of steel, in lieu of titanium, would result in cost savings. The proposal predicted that increases in weight and tooling costs by switching to steel would be offset by decreases in material costs and labor. Analysis of this proposal indicated that the resultant weight increases would be sizable and more or less confirmed proposal predictions. Lockheed-Georgia's policy of carefully considering value-of-a-pound-of-weight-saved on the C-5 program, however, led to the final conclusion that the weight increase was not acceptable and that the titanium straps were the most cost effective solution. Taking this a step further, if the damage tolerance straps were not incorporated into the design initially, the structure would undoubtedly be heavier. To provide the positive damage limiting effect of the titanium straps, some other recourse, such as heavier and thicker fuselage skins, would be needed. Aside from this consideration, the titanium damage tolerance straps share the structural load to the extent that they reduce the amount of skin material needed to satisfy static and other strength requirements.

In adopting damage tolerance design, ingenuity can be exercised to the effect that little or no weight penalties are incurred and additive cost increments are minimized. Even where initial damage tolerance design techniques call for increases in weight or costs, or both, alternate concepts are vigorously examined with a view to reducing these penalties to an insignificant level. Fortunately, at Lockheed-Georgia, this objective has been achieved in all designs within reasonable limits.

Most aircraft structures are inherently redundant in that a variety of load paths exist in their design. The additional time and effort to ensure that these redundancies satisfy damage tolerance requirements is a small price to pay for increased reliability and operational safety.

A multiplicity of design requirements often favor damage tolerance design. Flutter requirements, for example, may dictate a multispar wing design. Skin gages are often sufficient to minimize buckling under load, greatly alleviating the possibility of skin tears. Structural configurations, such as multi-support ribs, multi-control systems, and the like, are generally designed to accommodate requirements other than damage tolerance, but are inherently damage tolerant.

All things considered, Lockheed-Georgia experience strongly avows that positive gains resulting from incorporation of damage tolerance design in structures more than offsets the generally small costs and weight penalties incurred.

EFFECTS ON RELIABILITY AND MAINTAINABILITY

It is estimated that in incorporating damage tolerance design into the C-141 some 500 structural parts were added out of a total of approximately 320,000 parts. This represents a numerical increase of about 0.16 percent. Adding structure to a design increases overall complexity and can be expected to have some effect on overall reliability. When these additions enhance damage tolerance capabilities, however, the effect on reliability can be highly favorable.

As size and number of structural parts increase for larger aircraft, as for the C-5, more engineering opportunities exist to provide redundant load paths. Consequently, the number of parts added to meet damage tolerance requirements should be proportionately reduced.

Since all Lockheed-Georgia aircraft are designed for damage tolerance, the company does not have sufficient service experience with its own aircraft to provide a meaningful comparison with non-damage tolerance designs. Therefore, to assess effects on reliability and maintainability, resort is made to probability analysis.

By pooling various constant amplitude, random fatigue, and program test results, A. M. Freudenthal demonstrated that the probability density of fatigue cracking can be represented by a lognormal distribution where the standard deviation of the logarithm of the number of cycles to cracking exhibits only a slight dependence on fatigue life. (1)(2)

Let P(t) be defined as the ratio of non-cracked population to initial population (cumulative probability of cracking), where time t is measured in units of median time to crack; i.e., P(1) = 1/2. Then, the corresponding lognormal distribution may be integrated to yield:

$$P(t) = \int_0^t \frac{1}{\sqrt{2\pi} \cdot 2.0326\ \sigma u} \exp\left[-\left(\frac{\log_{10} u}{\sqrt{2}\ \sigma}\right)^2\right] du \quad (1)$$

$$= \frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{\log_{10} u}{\sqrt{2}\ \sigma}\right)\right]$$

where σ denotes the standard deviation of $\log_{10} t$, and the error function is defined by:

$$\operatorname{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x \exp(-t^2)dt \quad (2)$$

Equation (1) has wide applicability and is extremely convenient in that only a single relatively insensitive parameter, σ , need be specified.

Let P(t) represent the cumulative probability that a fatigue crack needing repair develops at time t in a single element structure so that the cracking of any one results in an abort (series configuration), then, the cumulative probability of abort for the n element configuration is given by:

$$S_n(t) = 1 - \left[1 - P(t)\right]^n \quad (3)$$

If, on the other hand, the elements are arranged so that cracking of all of them must occur to result in abort (parallel configuration), overall probability of abort is given by:

$$R_n(t) = \left[P(t)\right]^n \quad (4)$$

Figure 35 depicts curves representing the cumulative probability of abort for series and parallel configurations for the case $\sigma = 0.20$. This is a representative value taken from references 1 and 2. The abscissa of Figure 35 denotes the ratio of flight time to median single-element fatigue life.

Lockheed-Georgia attempts to design structures so that any single-element failure can occur without an abort. Suppose, however, that this were not the case. Referring to Figure 35, and assuming a fleet of 2000 aircraft with a service time of 25 percent of service life demonstrated by fatigue tests (point A, Figure 35), a probability exists that 2000 x .0015, or 3 aircraft, would have aborted if only one critical element were present. If the design contained 10 such critical elements (point B, Figure 35), the probability of abort enlarges to 2000 x .015, or 30 aircraft. To avoid aborts, it is clearly desirable to provide damage tolerance capabilities.

If these structures were not designed to be damage tolerant where a fatigue crack would lead to complete structural collapse, instead of the aborts there would likely be losses of aircraft. Losses of this magnitude would be prohibitive.

Figure 35 illustrates two major complementary phenomena accounting for the effectiveness of damage tolerance design in reducing abort probability to almost negligible proportions. These are related to the convergence and divergence of series and parallel curves, respectively, at low failure probabilities.

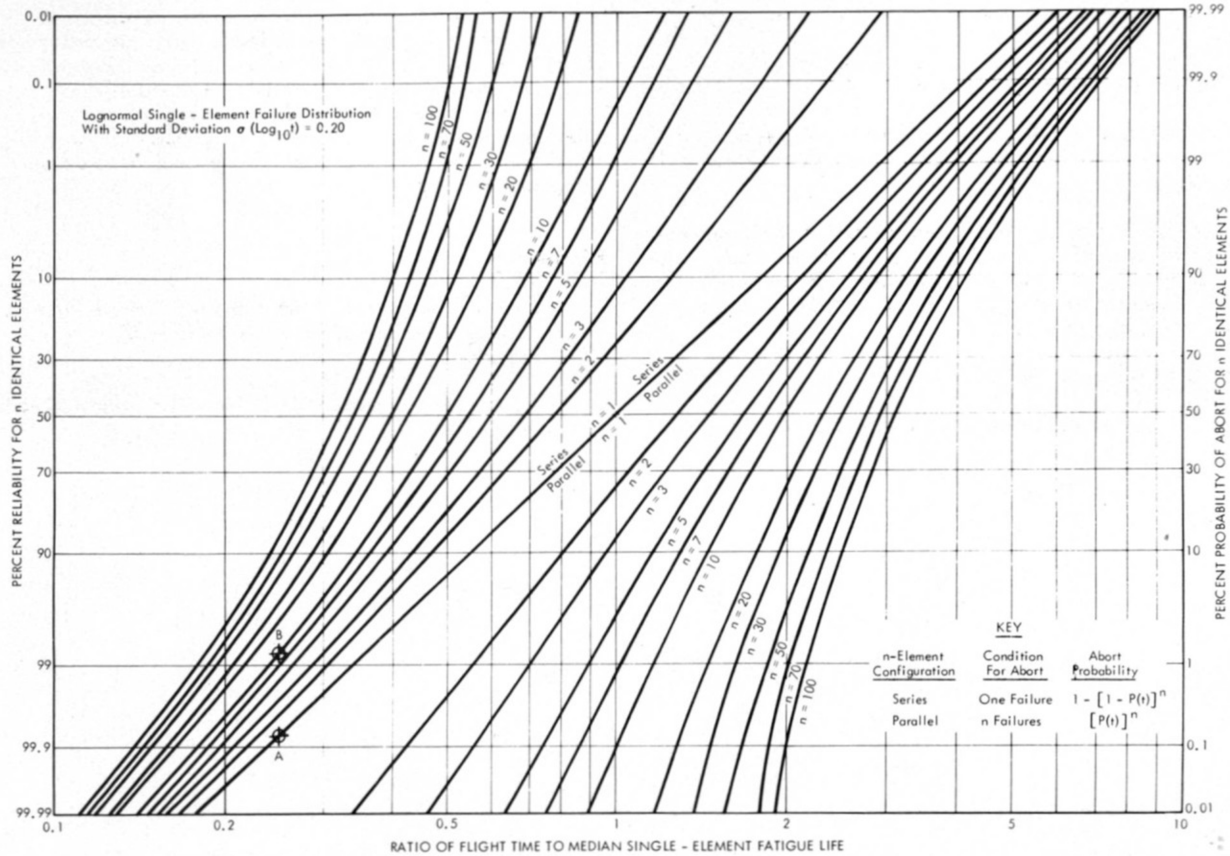


Fig. 35 - Abort Probability for Series and Parallel Configurations

Convergence of series configuration curves implies that many systems may be placed in series without severely reducing overall aircraft reliability if the reliability of each system is maintained at a high level.

On the other hand, divergence of parallel configuration curves indicates that the period of high reliability can be significantly extended for each system by introducing only a small number of parallel (redundant) elements as long at the failure probabilities of added elements remain small. This may be assured by frequent inspection or replacement of elements.

The left ordinate of Figure 35 indicates that the reliability of an aircraft with a single vulnerable element is 0.9985. With 10 vulnerable elements, this reduces to 0.985. Therefore, a given aircraft operating for 25 percent of demonstrated fatigue life would have a 99.85 percent chance of not experiencing an abort if it had only one critical element and only a 98.5 percent chance if it had 10 critical elements. Here again, damage tolerant design is necessary to achieve high reliability.

Where there are no catastrophically critical elements, the aircraft could be operated with assurance that periodic inspections will disclose potential problem areas prior to development of a dangerous situation. This has been the case with Lockheed-Georgia designed aircraft. Time and again, the C-130, for example, has experienced fatigue damage in service without catastrophic consequences and repairs have been made at the user's convenience without disruption of normal fleet operations.

Reliability and maintainability are closely related. Furthermore, an increase in the reliability confidence level becomes highly important if it is economically practical to operate the aircraft beyond its demonstrated service life, or if significant changes in operating patterns from the normal are experienced. If an aircraft is to be operated beyond its anticipated service life, reliability of the structure increasingly depends on damage tolerance design to compensate for increased probability of structural degradation caused by fatigue or corrosion.

SUMMARY

Damage tolerance design is a valuable asset at Lockheed-Georgia. The hard usage and harsh environments that the company's aircraft are subjected to in service has dictated adoption of damage tolerance concepts in all designs. In-service experience has proven the value of this approach in supplementing conventional design techniques.

Accordingly, the following steps relating to damage tolerance design are assiduously practiced at Lockheed-Georgia.

1. Every basic and ground load supporting structure is designed to be tolerant of a reasonable amount of damage, regardless of its cause.

2. Achievement of desired damage tolerance levels is demonstrated analytically and proven, where necessary, by structural tests.

3. Desired design fatigue life is analytically demonstrated with appropriate scatter factors. A factor of 4.0 is used where the analysis is supported by subcomponent tests. Where full scale components, such as fuselages, wings, and the like, are subjected

to fatigue tests, a factor of 2.0 is used in analysis.

4. The completed structure is subjected to complete airframe repeated load tests.

5. Finally, comprehensive maintenance inspection methods, periods, and procedures are established and recommended to the user.

By combining damage tolerance design with conventional fatigue resistance and repeated load techniques, aircraft designed and produced by Lockheed-Georgia have greatly enhanced reliability, maintainability, and operational safety characteristics.

Acknowledgments

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2. A. M. Freudenthal, WADD Technical Report 61-53, July, 1961.