AD A108145

CAST ALUMINUM PRIMARY AIRCRAFT STRUCTURE

C. K. Gunther

Boeing Aerospace Company
Boeing Military Airplane Development
Seattl' 'Vashington

F 33615-76-C-3111
Date: Dec. 1975

DTIC ELECTE DEC 1 1981 A

ABSTRACT

A A357 cast aluminum alloy forward fuselage pressure bulkhead has been developed and manufactured for the AMST-YC-14 aircraft. This work was performed by The Boeing Company under the direction of the AFFDL/AFML-AMS/ADP office as part of the Cast Aluminum Structures Technology (CAST) contract. The purpose of the program is to demonstrate that aluminum castings can be used for primary aircraft structural components with no weight penalty and a minimum of 30% cost savings.

To assist in the development of the design and in the demonstration of the structural integrity of the cast bulkhead, an extensive test program was undertaken to study the static strength, and fatigue and fracture characteristics of A357-T6 cast aluminum alloy. Static mechanical properties, S-N data, and crack growth and fracture toughness data were generated. The integrity of the design was demonstrated by analysis. The concepts of linear fracture mechanics were applied in the damage tolerance analysis. No casting factors were used in the design and analysis. Data were collected on the effects of defects commonly occurring in castings. Test coupons were removed from castings containing defects and subjected to repeated loads. The shift of the S-N curve for A357 aluminum alloy was determined for a number of typical defects. The effects of defects were also expressed as equivalent initial flaws assumed to be located at the defect site. Repair/no repair decisions for the production castings were based on an evaluation of the load environment and the effect of the defect on fatigue and fracture properties.

To further demonstrate the structural integrity of the casting, a full scale test program is being conducted. A cast bulkhead has been installed in a transition structure representing a portion of the forward fuselage of the YC-14 aircraft. Repeated loads representing four lives of design usage of the aircraft are applied for durability and damage tolerance testing. The adequacy of the design for static strength will be demonstrated on a second test article by static tests.

This document has been approved for public release and sale; its distribution is unlimited.

DTIC FILE COPY

NOMENCLATURE

a	=	Half crack length
C	=	Material constant
da/dN	=	Fatigue crack growth rate
DFR	=	Detail fatigue rating
f_{max}	=	Applied maximum cyclic stress
f_{mo}	=	Material constant
F_{ty}	=	Allowable tensile stress at yield
F_{tu}	=	Allowable ultimate tensile stress
K_{max}	=	Stress intensity factor at maximum cyclic stress
m	=	Material constant
n	=	Material constant
N	=	Structural life in terms of load cycles
R	=	Stress ratio
S	=	Material constant

Availability Codes
Avail and/or
Dist Special
A

Subscripts

o	=	Initial
f	=	Final

INTRODUCTION

Continually rising production costs of military and commercial aircraft have caused a reassessment of present fabrication methods for cost reduction. The cost-savings potential of castings is enormous. The lack of reproducibility and technical difficulties, however, have limited the application of casting technology to secondary structure. Increasing quantities of castings are being used in this application, though. The road blocks to the utilization of castings in primary structure have been questions of economics and safety. That is, lack of durability and damage tolerance have led to imposition of casting factors that penalize the weight of the component such that the casting process is not competitive with other fabrication methods.

The USAF, represented by the AFFDL/AFML-AMS ADP offices has sponsored the Cast Aluminum Structures Technology (CAST) program to develop the technology necessary for the application of castings to primary aircraft structure. Key objectives of the program are to restore designer confidence and to eliminate the casting factor. This is to be accomplished by developing and fabricating a cast primary aircraft structure component without a weight penalty, by demonstrating a minimum of 30% cost savings, and by proving the casting structural integrity. This paper describes the efforts required to demonstrate the structural integrity of cast primary structure by using the demonstration component of the CAST program as an example.

The component selected for the demonstration of t... ...ogy emerging from the CAST program is the forward fuselage ...ead ... Boeing YC-14 aircraft (Fig 1). This structure meets all ... the ...ments for a successful demonstration of the technology. The bulkhead is a safety-of-flight structure since it forms part of the fuselage pressure vessel and provides the nose gear support. It is a large complex structure replacing many parts of fabricated wrought products therefore having great potential for cost savings. It can be tested at reasonable cost because of its location on the aircraft. A total of 20 bulkheads were produced, 10 by the Boeing foundry and 10 by Hitchcock Industries, Inc. to demonstrate reproducibility of the process and ability to transfer the technology to another foundry. The aluminum alloy selected for the casting is A357. The cast bulkhead (Fig 2) measures approximately 2.29 m (7.5 ft) by 1.37 m (4.5 ft). It is designed to replace the original built-up bulkhead without requiring modifications to the surrounding structure. The bulkhead consists of a frame chord with a corrugated web in the upper pressurized portion and a flat web, stiffened by horizontal and vertical stiffeners, in the lower half of the bulkhead. Attachment lugs for the nose gear support structure are located across the bulkhead where the flat and corrugated webs meet. The bulkheads were cast vertically in composite sand/chill molds and casting tolerances were extremely challenging. For overall dimensions, tolerances of ±1.52 mm (0.06 in.) had to be met. Other challenges were the thin webs. The major portion of the webs is only 2.54 mm (0.1 in.) thick. The bulkheads were completely inspected by radiography and penetrant after cleanup. The thick lug sections were inspected by ultrasound. A number of defects and minor misruns were present in the bulkheads destined for full scale testing. These were corrected by welding and success was verified by radiographic and penetrant inspection. The two test bulkheads were then heat treated to the T6 condition and again penetrant inspected for cracks. The bulkheads were then machined. Only a minimum of machining was required. The chord member was milled to outside fuselage contour and the attachment lugs were line bored and milled to thickness. A final penetrant inspection was conducted during which a number of cracks not exceeding 6.35 mm (0.25 in.) in length were discovered. In consideration of the effects of these defects, as will be described later, it was predicted that these cracks would not degrade the integrity of the casting below the requirement. Also by a similar consideration, some porosity in isolated areas was not repaired. A series of quench cracks was discovered in the flat web in the lower half of the durability test bulkhead just prior to the start of testing. Repairs could have been carried out but, since an analysis showed that these cracks would not grow to critical size within the planned test period, they were left unrepaired. In order to protect the test bulkheads against corrosion, they were dipped into an alodine bath.

The structural integrity of the cast bulkhead was demonstrated in accordance with Reference 1 as described in the following paragraphs.

MATERIAL DATA

The static mechanical properties and the fatigue and fracture behavi... of materials used in primary aircraft structure must be known adequately to achieve the desired levels of strength, durability, and damage tolerance. When the CAST program was started, little data was available on A357 aluminum alloy. Therefore, an extensive test program was undertaken concurrently with the design and development phase to increase this data base. The objective of this work is to develop static design a...wables information suitable for consideration for MIL-HDBK-5. Specimens for static mechanical properties testing were removed from castings that resemble a portion of the bulkhead. Two different castings, designated Part A and B, were sampled for specimens. Approximately 350 tension tests were conducted to develop design properties of the bulkhead and with these data the effects of physical and process variables

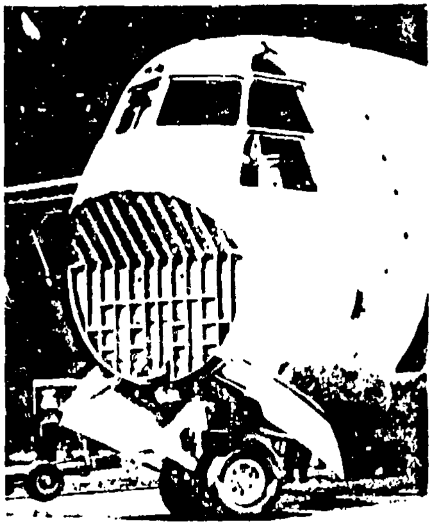


Figure 1. Boeing YC14 aircraft--forward fuselage bulkhead

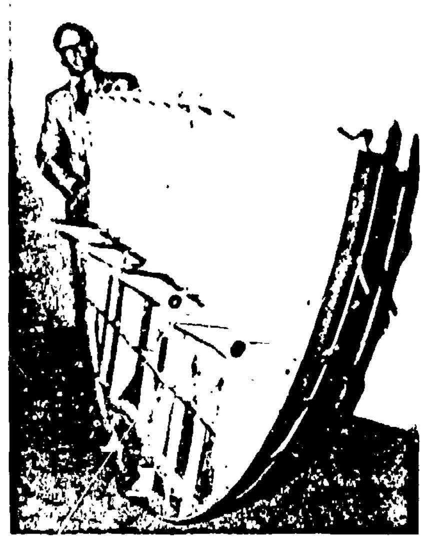


Figure 2. Cast bulkhead

were examined. About 250 compression, shear, and bearing tests were conducted on specimens removed from the castings adjacent to zones for which tensile data was obtained. Table 1 presents a summary of the tensile properties. The values quoted are average values. Since the average properties derived from either casting (A and B) are essentially the same, all data was combined for the derivation of a single set of allowables. For a statistical A-basis level of assurance, the following allowables were obtained:

$$F_{tu} = 290 \text{ MPa } (42 \text{ ksi}), \quad F_{ty} = 248 \text{ MPa } (36 \text{ ksi})$$

Type Casting	Part A						Part B		
Property (units)	TUS [3] ksi		TYS [3] ksi		EL [1] %		TUS [3] ksi	TYS [3] ksi	EL [1] %
Foundry [2]	B	H	B	H	B	H	B	B	B
Critical areas	48.5	48.9	40.6	40.3	4.4	4.3	46.5	40.2	2.3
Other areas	46.5	46.7	41.1	40.4	2.3	2.4	48.1	41.7	3.0
Combined	47.2	47.4	40.9	40.4	3.0	3.0	47.6	41.2	2.8

[1] Elongation obtained from full range stress-strain curves

[2] B = Boeing; H = Hitchcock

[3] ksi to MPa, FACTOR = 6.895

Table 1. Tensile property summary, A357-T6 casting, average values

These present the lowest common denominator of allowables for all areas of the bulkhead. For a more detailed treatment of the allowables program, see Reference 2.

Because mechanical properties of castings vary by location and depend on the casting geometry and numerous parameters associated with foundry methods, it appears more sensible to assign different allowables to different zones of castings. One approach would be to cut up a number of castings prior to production and to derive allowables for a number of zones of this casting. Unfortunately, allowables would then be only good for a particular casting produced by the same foundry. A better approach is to relate mechanical properties to nondestructive inspection results. For example, as was shown in Reference 3, the tensile properties depend significantly on dentrite arm spacing (DAS) and on degree of porosity as e.g., measured by ASTM E155 soundness grades. These allowables would be independent of casting geometry and other foundry parameters. Such a system could be universally applied and would be very economical. Once derived, all foundries would benefit from it. Table 2 presents an example of such dual base (DAS and soundness) allowables for A357.

DAS RANGE 0.0001 in. [1]		SOUNDNESS GRADE (ASTM E155)					
		A		B		C	
		AVG	A-VALUE	AVG	A-VALUE	AVG	A-VALUE
Up to 12	F_{tu}(ksi) [2]	50.0	45.9	48.5	44.4	47.7	43.6
	F_{ty}(ksi)	40.6	36.5	40.6	36.5	40.6	36.5
	e (%)	4.8	1.9	2.6	1.0	2.6	1.0
13 to 18	F_{tu}(ksi)	48.3	44.2	47.0	42.9	46.2	42.1
	F_{ty}	40.6	36.5	40.6	36.5	40.6	36.5
	e	3.4	1.3	1.8	0.7	1.8	0.7
19 to 24	F_{tu}	47.0	42.9	45.7	41.6	44.9	40.8
	F_{ty}	40.6	36.5	40.6	36.5	40.6	36.5
	e	2.2	0.9	1.3	0.5	1.3	0.5
25 to 30	F_{tu}	46.4	42.3	45.0	40.9	44.2	40.1
	F_{ty}	40.6	36.5	40.6	36.5	40.6	36.5
	e	1.7	0.7	1.0	0.4	1.0	0.4

NOTE: A357-T6 castings having extreme chemical constituent limits and/or heat treatment processing parameters may exhibit significantly different tensile properties

[1] in. to mm, FACTOR = 25.4
[2] ksi to MPa, FACTOR = 6.895

Table 2. Dual basis tensile properties for A357-T6

The fatigue behavior of A357 aluminum alloy subjected to constant amplitude loading was studied by testing notched (K_t = 3.0) and unnotched specimens. The specimens were fabricated from cast plates. Approximately 150 specimens were tested. A typical set of data is presented as an example. Table 3 presents smooth fatigue, and Table 4 presents notched fatigue data.

Specimen Identification	Casting Number	f_{max} ksi	f_{min} ksi	R	N Cycles to Failure	Environment °F/% RH	Remarks
DSSN 1-1	601A	24	1.44	0.06	148,000	71/18	
DSSN 1-2	601B	24	1.44	0.06	198,000	72/18	
DSSN 1-3	606C	24	1.44	0.06	205,000	72/18	
DSSN 1-4	619A	24	1.44	0.06	167,000	72/18	
DSSN 1-5	619B	24	1.44	0.06	269,000	72/18	
DSSN 1-6	619C	24	1.44	0.06	299,000	70/08	
DSSN 1-7	608A	20	1.20	0.06	320,000	70/08	
DSSN 1-8	608B	20	1.20	0.06	109,000	70/08	
DSSN 1-9	608C	20	1.20	0.06	478,000	70/08	
DSSN 1-10	613A	16	0.96	0.06	1,949,000	70/08	Failed outside test area
DSSN 1-11	613B	16	0.96	0.06	652,000	70/12	
DSSN 1-12	613C	16	0.96	0.06	592,000	70/18	
DSSN 1-13	631A	16	0.96	0.06	2,721,000	70/20	
DSSN 1-14	631B	16	0.96	0.06	5,215,000	72/36	No failure
DSSN 1-15	631C	16	0.96	0.06	5,146,000	71/26	No failure

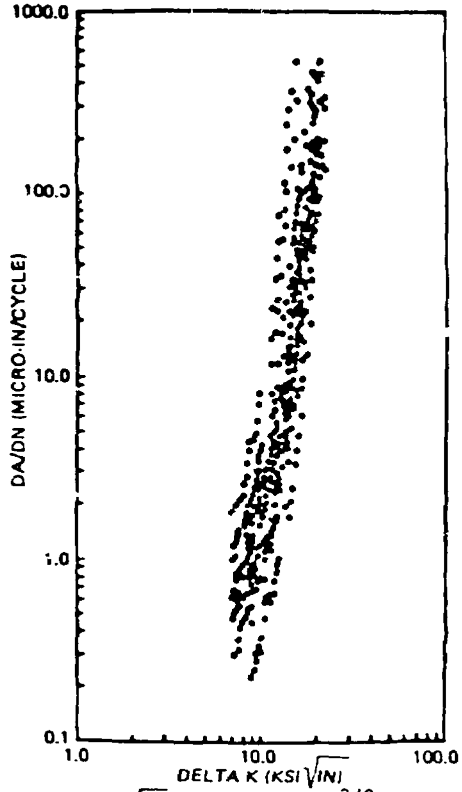
Test Machine: SF-10-U #5 Cyclic Wave Form: Sine
Cyclic Frequency: 30 cps Conversion: ksi to MPa, FACTOR = 6.895

Table 3. A357 - smooth fatigue data (k_t = 1.0)

Specimen Identification	Casting Number	f_{max} ksi	f_{min} ksi	R	N Cycles to Failure	Environment °F/% RH	Remarks
DSSN 1-1	601D	18	1.08	0.06	50,000	76/40	
DSSN 1-2	601E	18	1.08	0.06	73,000	76/38	
DSSN 1-3	606F	18	1.08	0.06	46,000	76/38	
DSSN 1-4	619D	18	1.08	0.06	71,000	76/35	
DSSN 1-5	619E	18	1.08	0.06	82,000	76/38	
DSSN 1-6	619F	18	1.08	0.06	87,000	76/36	
DSSN 1-7	608D	16	0.96	0.06	129,000	76/36	
DSSN 1-8	608E	16	0.96	0.06	89,000	76/36	Grip and hole failure
DSSN 1-9	608F	16	0.96	0.06	83,000	76/36	
DSSN 1-10	613D	14	0.84	0.06	83,000	76/36	
DSSN 1-11	613E	14	0.84	0.06	236,000	76/36	
DSSN 1-12	613F	14	0.84	0.06	215,000	76/36	
DSSN 1-13	631D	14	0.84	0.06	307,000	76/41	
DSSN 1-14	631E	14	0.84	0.06	373,000	76/35	
DSSN 1-15	631F	14	0.84	0.06	214,000	76/37	

Test Machine: SF-10-U #5 Cyclic Wave Form: Sine
Cyclic Frequency: 30 cps Conversion: ksi to MPa, FACTOR = 6.895

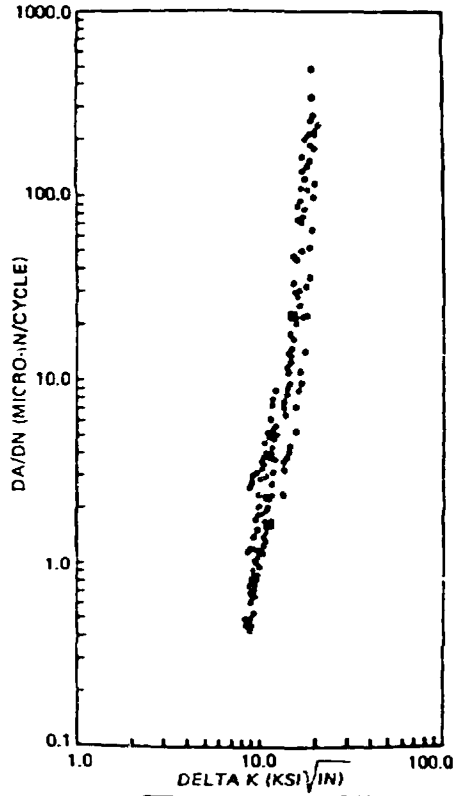
Table 4. A357 - notched fatigue data (k_t = 3.0)



1 KSI$\sqrt{IN}$ = 1.0988 $MN/M^{3/2}$

1 IN = 25.4 mm

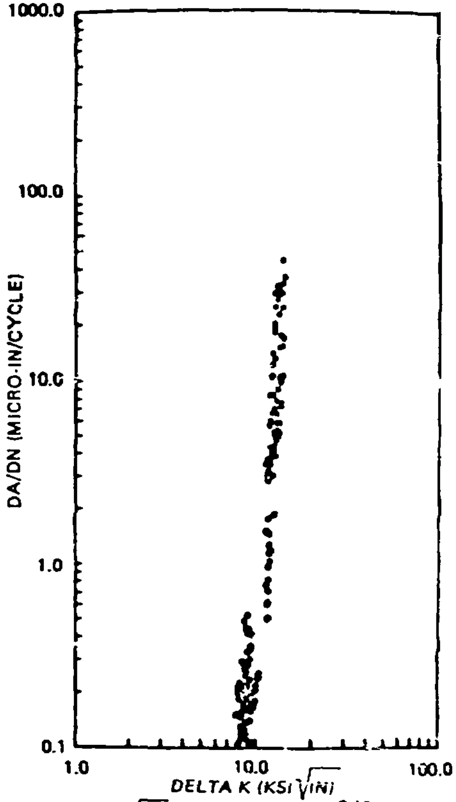
Figure 3. A357 crack growth rate data, lab air



1 KSI$\sqrt{IN}$ = 1.0988 $MN/M^{3/2}$

1 IN = 25.4 mm

Figure 4. A357 crack growth rate data, 90% RH



1 KSI$\sqrt{IN}$ = 1.0988 $MN/M^{3/2}$

1 IN = 25.4 mm

Figure 5. A357 crack growth rate data, $-65^{o}F$

The crack growth behavior was studied by testing compact type (ASTM E399) specimens. Approximately 50 specimens were fabricated from cast plates and tested. The data were reduced according to ASTM E24 recommendations. Crack growth rates were expressed as:

$$da/dN = C\ (1-R)^{m}\ (K_{max}\ )^{n} \quad (1)$$

The constants C, m, and n were determined by least-square fitting of the data. The results of 15 specimens tested in laboratory environment are shown in Figure 3. The effect of high relative humidity (90%) and low temperature 219 K (-65°F) are shown in Figures 4 and 5 respectively. An examination of the results shows that the crack growth rates in A357 are not much affected by either humidity or low temperature.

Tests were also performed to characterize the fracture toughness of the alloy. Plane-strain fracture toughness tests were conducted according to ASTM Standard Test Method, E399. Approximately 30 compact specimens were machined from cast blocks and tested in laboratory environment and at 219K (-65 F). Typical results are summarized in Table 5. The fracture toughness of thin castings was investigated by testing center-cracked panels. Approximately 30 panels 0.51 m (20 in.) x 1.02 m (40 in.) of 5.1 mm (0.2 in.) thickness were cast and tested in laboratory environment and at 219 K (-65 F). Typical results are presented in Table 6.

The fatigue and fracture properties should also be related to DAS and soundness of casting zones as was done for the static properties. However, not enough data is available yet to investigate whether or not DAS and soundness significantly influence these properties.

EFFECTS OF DEFECTS

It is possible that material defects may be present in finished castings as a consequence of the fabrication process. The uncertainty associated with the effects of the defects on the casting service life has led, among other reasons, to the application of casting design factors. These casting factors penalize the application through added weight and make castings, although attractive from a cost point of view, less competitive in aircraft structures. If sufficient knowledge were gained about the effects of defects in service, they could be dealt with in a more direct manner instead of by reducing the overall stress level and penalizing the whole casting whether a defect is present or not.

Material defects may adversely affect the performance of an aircraft in service and may pose a threat to the safety of flight. The United States Air Force has recognized this and issued a specification concerning damage tolerance of primary aircraft structure (4). This specification requires that "initial flaws be assumed as a result of material and structure manufacturing and processing operations." Contractors are required to demonstrate that these initial flaws placed in the most critical location do not result in catastrophic failures when subjected to the design flight-by-flight stresses and chemical/thermal environment.

The damage tolerance specification applies to structures made from wrought metals. It is foreseen that a similar specification could be developed for castings to be used in primary aircraft structure. Although castings in this application will be required to be fully inspected by nondestructive radiographic and by penetrant techniques, cast primary aircraft structure must be designed to be able to tolerate certain types and dimensions of casting defects in the most critical location(s) in the event that a defect may not be detected. If a defect is known to exist in a casting, information concerning the effects of the defect could also be used for repair/no repair decisions. If a defect is found in a location where the load environment is such that the defect would not grow to a critical size in service, the part would not have to be repaired. Cost savings would also be realized in a situation where a defect is located in a part such that a repair is not feasible. Instead of scrapping an expensive component, one would evaluate the criticality of the defects.

A study of the effects of defects was undertaken and is continuing as part of the efforts in characterizing the fatigue and fracture behavior of A357 aluminum alloy castings. Radiographs of castings, resulting from the manufacturing methods development portion of the CAST program, were reviewed for suitable defects. Specimen blanks were cut from a defect areas. Since defects tend to occur where rapid changes in cross-sections take place, it was difficult to obtain a desired number of specimens for a specific type of defect. All specimens were fatigue cycled to failure at constant load amplitudes.

Two separate approaches were used for analyzing the results in order to propose different techniques for evaluating the damage tolerance levels of castings. These two approaches are:

- o Fatigue rating approach
- o Equivalent initial flaw approach

Specimen Identification	TYS ksi	W in.	B in.	a in.	P_{max} lb	P_Q lb	P_{max}/P_Q	K_Q ksi$\sqrt{in.}$	$2.5\left(\frac{K_Q}{TYS}\right)^2$	RSC	Environment °F/% RH	Remarks
ACT1-1	41	1.5	0.710	0.813	1695	1625	1.04	20.5	0.611	0.93	72/36	
ACT1-2	41	1.5	0.713	0.777	1000	1000	1.0	11.6	0.196	0.49	72/36	
ACT2-1	40	1.5	0.700	0.717	1795	1665	1.08	17.5	0.485	0.78	72/36	
ACT2-2	40	1.5	0.707	0.770	2240	2160	1.04	24.9	0.981	1.13	72/36	
ACT3-1	42	1.5	0.762	0.680	1625	1590	1.02	14.3	0.287	0.55	72/35	
ACT3-2	42	1.5	0.744	0.667	1965	1845	1.07	16.6	0.386	0.66	72/36	Valid K_{IC}
ACT4-1	41	1.5	0.756	0.640	1750	1590	1.10	13.5	0.277	0.56	72/36	
ACT4-2	41	1.5	0.757	0.660	1995	1830	1.09	16.0	0.390	0.67	72/36	Valid K_{IC}
ACT5-1	36	1.5	0.690	0.717	2115	1930	1.10	20.6	0.828	1.04	72/36	
ACT5-2	36	1.5	0.690	0.663	2000	1775	1.13	17.2	0.557	0.85	73/36	
ACT6-1	39	1.5	0.690	0.803	2400	2225	1.08	28.3	1.317	1.40	72/36	
ACT6-2	39	1.5	0.690	0.800	2220	2055	1.08	25.9	1.103	1.28	72/36	
ACT7-1	42	1.5	0.714	0.737	1900	1810	1.05	19.4	0.544	0.82	72/36	Valid K_{IC}
ACT7-2	42	1.5	0.712	0.757	1955	1860	1.05	20.8	0.625	0.90	72/36	
ACT8-1	38	1.5	0.752	0.710	2050	1885	1.09	18.2	0.564	0.85	72/36	Valid K_{IC}
ACT8-2	38	1.5	0.735	0.727	2155	1950	1.11	19.9	0.674	0.95	72/36	
DCT1-1	40	1.5	0.746	0.810	2345	2265	1.04	26.8	1.147	1.258	70/46	
DCT1-2	40	1.5	0.746	0.723	2625	2625	1.00	26.3	1.100	1.102	70/46	
DCT1-3	40	1.5	0.747	0.770	2470	2520	1.02	26.3	1.106	1.174	70/32	
DCT1-4	40	1.5	0.748	0.770	2730	2545	1.07	27.6	1.219	1.295	70/32	
DCT1-5	40	1.5	0.746	0.891	1635	1635	1.00	23.7	0.894	1.162	70/46	
DCT2-1	40	1.5	0.746	0.742	2465	2237	1.10	23.0	0.843	1.075	-65	
DCT2-2	40	1.5	0.750	0.759	2340	2290	1.02	24.3	0.942	1.074	-65	
DCT2-3	40	1.5	0.750	0.753	2350	2340	1.00	24.5	0.960	1.059	-65	
DCT2-4	40	1.5	0.745	0.745	2345	2275	1.03	23.7	0.892	1.041	-65	
CDT2-5	40	1.5	0.746	0.810	2010	1855	1.08	22.0	0.768	1.077	-65	

Conversion: ksi to MPa, FACTOR = 6,895
in. to mm, FACTOR = 25.4
ksi$\sqrt{in}$ to $\frac{MN}{m^2}\sqrt{m}$ FACTOR = 1.099
lb to N, FACTOR = 4.45

Table 5. A357 - plane strain fracture toughness data

Specimen Identification	Thickness t, in.	Width w, in.	Initial Crack Length $2a_o$ in.	Critical Crack length $2a_c$ in.	Failure Stress f_c ksi	K_{app} ksi$\sqrt{in.}$	K_C ksi$\sqrt{in.}$	TYS ksi	Net Section Stress f_{net} ksi	Environment °F/% RH	Remarks
ACC1-1	0.193	20.0	4.16	5.38	14.1	36.1	47.4	41.5	19.3	72/37	
ACC1-2	0.200	20.0	4.00	6.64	13.8	34.7	47.1		20.7	72/31	
ACC2-1	0.211	20.0	4.02	4.66	16.4	41.4	45.2	39.8	21.4	68/38	
ACC2-2	0.205	20.0	4.00	4.96	18.2	45.8	51.6		24.2	71/35	
ACC3-1	0.221	20.0	4.00	6.72	15.8	39.8	54.1	42.2	23.9	76/40	
ACC3-2	0.186	20.0	4.26	5.86	16.5	42.9	51.8		23.3	74/40	
ACC4-1	0.201	20.0	4.02	4.76	14.2	35.9	39.0	40.5	18.7	74/38	
ACC4-2	0.207	20.0	3.96	5.16	14.1	35.2	39.8		19.0	74/40	
ACC5-1	0.208	20.0	4.00	5.42	18.0	45.2	53.9	35.8	24.6	72/49	
ACC5-2	0.202	20.0	4.08	6.95	16.1	40.9	55.5		24.7	71/37	
ACC6-1	0.203	20.0	4.02	7.91	20.4	52.2	77.6	39.0	33.7	72/36	$f_{net} > 0.8TYS$
ACC6-2	0.202	20.0	4.00	5.64	17.9	45.0	54.7		24.9	74/36	
ACC7-1	0.198	20.0	4.40	-	18.7	49.4		41.6	-	71/38	
ACC7-2	0.202	20.0	3.50	-	14.9	35.0	-		-	70/33	
ACC8-1	0.213	20.0	4.00	5.20	11.8	29.7	33.8	38.3	15.9	73/43	
ACC8-2	0.206	20.0	4.10	5.80	9.4	23.9	28.7		13.2	70/43	
DCC1-1	0.194	20.0	4.08	5.50	17.41	44.8	52.6	40	24.0	71/40	
DCC1-2	0.181	20.0	4.01	5.60	19.76	50.5	60.6	40	27.4	72/43	
DCC1-3	0.203	20.0	3.99	5.50	16.63	42.4	50.9	40	22.9	72/42	
DCC1-4	0.201	20.0	5.31	7.66	15.99	47.7	59.7	40	25.9	70/41	$2a_c > w/3$
DCC1-5	0.202	20.0	4.08	6.82	24.54	63.2	83.8	40	37.2	72/38	$2a_c > w/3$
DCC2-1	0.231	20.0	4.12	4.38	8.31	21.5	22.3	40	10.6	-65	
DCC2-2	0.188	20.0	5.47	8.38	13.81	41.8	54.3	40	23.8	-65	$2a_c > w/3$

Conversions: ksi to MPa, FACTOR = 6,895
in. to mm, FACTOR = 25.4

ksi$\sqrt{in.}$ to $\frac{MN}{m^2}\sqrt{m.}$ FACTOR = 1.099

Table 6. A357 - fracture toughness data of thin sections

FATIGUE RATING APPROACH TO EFFECTS OF DEFECTS

In this approach the results of the experiments are used to derive S-N curves for each type of defect tested. S-N curves can be expressed as

$$f_{max} = f(N, DFR, R, S, f_{mo}) \qquad (2)$$

Using the predetermined material fixed parameters, DFR's can be derived for each group of specimens representing a type of defect. Table 7 lists the derived fatigue ratings. The reduced DFR's for the various defects in comparison to the reference DFR are an indication of the stress concentrations caused by the defects. The effects of the defects are evaluated by performing life predictions using the appropriate S-N curves as determined by the DFR and by comparing the results with the service life requirement.

EQUIVALENT INITIAL FLAW APPROACH TO EFFECTS OF DEFECTS

The effect of defects could be simulated analytically by the assumption of a mathematically convenient shaped flaw at the location of the defect. The growth of these flaws subjected to the service repeated loads and chemical/thermal environment is predicted utilizing the basic material crack growth behavior. This is typically described as

$$da/dN = C\,(1-R)^m \quad (K_{max})^n \qquad (3)$$

DEFECT TYPE/X-RAY GRADE	NUMBER OF SPECIMENS	DFR [1]	DFR NORMALIZED
POROSITY/B	6	20.1	0.96
POROSITY/C	6	16.1	0.77
POROSITY-SPONGE-SHRINKAGE/W	4	14.1	0.67
POROSITY-INCLUSION/C	2	17.2	0.82
POROSITY-INCLUSION/W	1	15.6	0.74
POROSITY-SLAG/B	1	16.7	0.80
POROSITY SLAG/C	1	16.4	0.78
SLAG/B	1	15.9	0.76
SLAG/W	2	15.9	0.76
DEFECT FREE (REFERENCE VALUE)		21.0	1.0

[1] DFR = detail fatigue rating for 95% confidence and 95% reliability in survival of the detail

Table 7. Fatigue ratings for defects

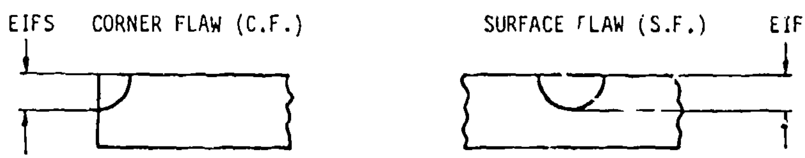
Lives are predicted by integrating this expression, i.e. for constant stress amplitudes,

$$N = \frac{1}{C(1-R)^{m}} \int_{a_0}^{a_f} \frac{da}{(K_{max})^{n}} \tag{4}$$

where N is the life in number of cycles it takes the flaw to grow from the initial flaw dimension, a_0, to the final dimension, a_f. For the derivation of an equivalent initial flaw, N and a_f are known and the above equation must be solved for a_0. This can easily be accomplished using any quadrature routine.

Equivalent initial flaws were derived from the fatigue test results. Depending on the failure origin, either semi-circular surface flaws or quarter-circular corner flaws were assumed. A transition to a through-the-thickness crack was made when the flaw depths reached the specimen thickness. The final dimension a_f was assumed equal to the specimen width. The characteristic lives of each group of specimens were used in the analysis. Table 8 summarizes the results. The effects of the defects are evaluated by assuming the equivalent initial flaws at the defect location and by predicting flaw growth as the result of the service usage. The resulting life is then compared to the service life requirement.

DEFECT TYPE/X-RAY GRADE	NUMBER OF SPECIMENS	INITIAL FLAW TYPE	EIFS in. [1]
POROSITY/B	4	S.F.	0.064
POROSITY/B	2	C.F.	0.061
POROSITY/C	5	S.F.	0.081
POROSITY/C	1	C.F.	0.074
POROSITY-SPONGE-SHRINK/W	4	S.F.	0.090
POROSITY-INCLUSION/C	2	S.F.	0.074
POROSITY-INCLUSION/W	1	S.F.	0.095
POROSITY-SLAG/B	1	S.F.	0.075
POROSITY-SLAG/C	1	S.F.	0.077
SLAG/B	1	S.F.	0.078
SLAG/W	2	S.F	0.081



[1] in. to mm, FACTOR = 25.4

Table 8. Equivalent initial flaws for defects

STRUCTURAL ANALYSIS

The structural integrity of the cast bulkhead was first demonstrated by analysis (5). A stress analysis was performed using the finite element technique. The bulkhead and surrounding structure were idealized by plate, beam and rod elements as shown in Figure 6. The finite element solutions yielded the internal stresses that are in equilibrium with the external loads such as nose gear loads and pressurization. The bulkhead was checked for strength using the generated allowables. No casting factors were employed. The bulkhead was also analyzed for durability using a conventional fatigue approach. Fatigue damage was calculated for the repeated loads due to the design service environment of the YC-14 aircraft. The structural life of the bulkhead was predicted using the Palmgren-Miner cumulative damage theory. The results indicated that the life of the strength designed bulkhead exceeds the design service life of 25,000 hours by 4%. This prediction includes factors corresponding to 95% confidence and 95% reliability.

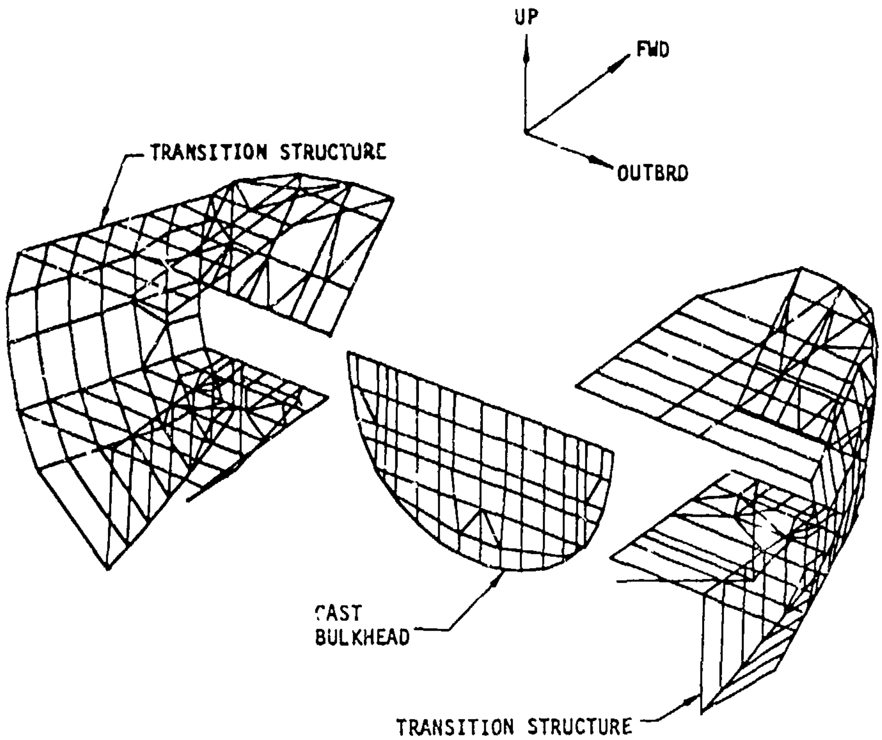


Figure 6. Finite element model of bulkhead and transition structure

The casting was also analyzed for damage tolerance. Initial flaws were assumed to be located at the most critical locations in accordance with Reference 4. Crack growth was predicted for the assumed initial flaws subjected to the repeated loads of the design service environment. The results indicated that none of the assumed initial flaws would grow to critical size in two design service lives. Therefore, the damage tolerance requirements were met. Adequate structural integrity was demonstrated by the above analyses.

FULL SCALE TESTING

A further demonstration of structural integrity is being conducted by full scale testing at Wright-Patterson Air Force base. The objective is to demonstrate by test that the casting possesses adequate structural integrity. In particular, durability tests are being conducted to demonstrate that the economic life of the bulkhead is equal to or greater than the design service life under design usage. The economic life of a structural component is typically determined by the occurrence of widespread cracking and by that time at which it is no longer economical to repair the structure. Damage tolerance tests and static tests will be conducted to demonstrate that the requirements of Reference 4 and 6 respectively are met.

The full scale test setup is shown in Figure 7. The bulkhead is attached to a transition structure in order to simulate the surrounding fuselage structure of the YC-14 aircraft. The upper portion of the structure is pressurized. Test loads other than pressurization are applied by hydraulic actuators through a simulated nose gear trunnion support structure.

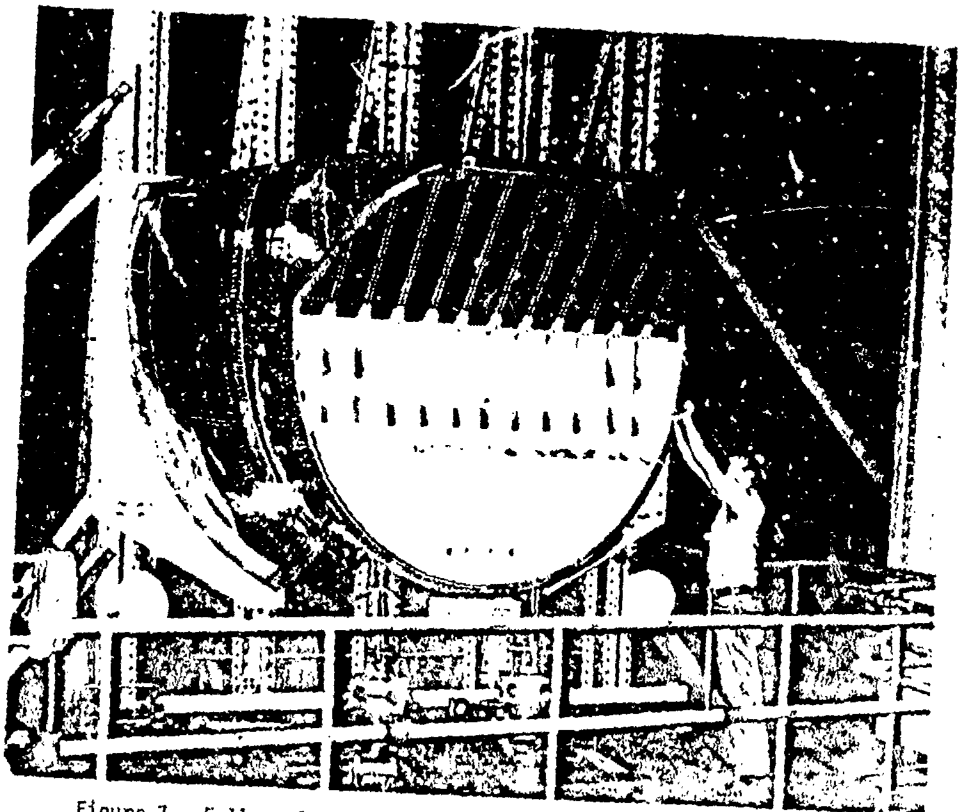


Figure 7. Full scale test set-up at Wright-Patterson Air Force Base

Durability testing was begun in December, 1978. The design usage is simulated by application of appropriate repeated loads. The test plan calls for four lifetimes of durability testing, of which two lives were completed in March, 1979. No defect growth or new flaw initiation had occurred up to that time. Artificial damage was therefore introduced by saw cutting for the purpose of damage tolerance testing. This testing is presently being conducted concurrently with the third and fourth lives of durability testing.

A second bulkhead will be installed into the transition structure for static tests. The bulkhead will be subjected to two ultimate conditions; spring-back landing and landing with lateral load. The objective is to demonstrate that the casting is capable of sustaining 150 percent of the limit loads corresponding to the above conditions.

CONCLUSIONS AND RECOMMENDATIONS

During the course of the CAST program, a CAST primary aircraft structure component was produced without a weight penalty and its structural integrity was demonstrated by analysis. The results of the full scale test program to date indicate that the structural integrity of the bulkhead will also be substantiated by test. These accomplishments have to be viewed in light of the fact that the test bulkheads were not produced under any special consideration but were typical. The test articles contained more defects than desired due in part to the imperfect nature of the nondestructive inspection methods available today and due to some design deficiencies. Nevertheless, the CAST program has demonstrated that castings can be used in primary aircraft structure. Considering the cost savings offered by this casting technology (35% for 300 bulkheads compared to the cost of the built-up bulkhead), and a successful test program, the next step appears to be the demonstration of a structure component in service. Before this step is taken, however, additional developmental work is required. In particular, the non-destructive evaluation of static mechanical and fatigue and fracture properties of castings must be developed. Also, more data should be generated concerning the effects of defects to enable designers to deal with them with confidence. A follow-on program is planned to identify the physical and process variables that significantly influence elongation. The objective of this program is to improve the minimum elongation of castings.

REFERENCES

1. Military Standard, Aircraft Structural Integrity Program Airplane Requirements, MIL-STD-1530A.

2. Cast Aluminum Structures Technology, Manufacturing Methods--Phase II, AFFDL-TR-78-62, May 1978.

3. McLellan, D. L., Tensile Properties for A357-T6 Aluminum Castings, submitted to ASTM for publication in Journal of Testing and Evaluation.

4. Military Specification, Airplane Damage Tolerance Requirements, MIL-A-83444 (USAF).

5. Cast Aluminum Structures Technology, Phase III, AFFDL-TR-78-7, January 1978.

6. Military Specifiation, Airplane Strength and Rigidity, General Specification for, MIL-A-008860 (USAF).