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SECTIONALIZED MAIN ROTOR BLADE ADVANCED DESIGN STUDY

Tadeusz Tarczynski

Boeing Company

Prepared for:

Army Air Mobility Research and Development Laboratory

August 1972

AD

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By

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August 1972

EUSTIS DIRECTORATE
U. S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

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THE BOEING COMPANY, VERTOL DIVISION
PHILADELPHIA, PENNSYLVANIA

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13. ABSTRACT

This report covers a study undertaken for the advanced design of a sectionalized main rotor blade. After investigation of the whole spectrum of design arrangements, a bolted-together design (with field replaceable boxes, L.E. tip and trailing edge) was chosen. For direct replacement of existing blades, a bolted design was selected with essentially the same dynamic rotor characteristics of the current production blade. The parameters that were closely matched to achieve this were: natural frequency, loads, and dynamic balance axis. A cost increase of approximately 50 percent is indicated over present UH-1H rotor blades to match current design features, utilizing ground rules on inherent and external damage specified by the procuring agency.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Rotor Blade Rotor Blade Maintainability Rotor Blade Repairability Rotor Blade System Costs Sectionalized Rotor Blade UH-1						

II

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FORT EUSTIS, VIRGINIA 23604

This is one of a number of parallel studies examining various rotor blade design concepts emphasizing reliability and maintainability. Other concepts under study are repairable and expendable rotor blade designs. These design studies are aimed at improving rotor blade R&M characteristics, thereby reducing life cycle cost. To achieve comparability, all blade designs are required to match UH-1D/H characteristics, and life cycle cost is compared to that for the UH-1D/H.

This particular study examined a sectionalized concept wherein repairability would be achieved through field replacement of blade leading- and trailing-edge segments. The concept was subjected to a detailed R&M analysis which included consideration of external damage rates experienced by the UH-1D/H fleet.

The selected rotor blade concept proved to have a significantly higher life cycle cost than the present design. We concur that this design is not cost effective for a UH-1D/H application.

When considering the applicability of the sectionalized rotor blade design to rotor systems other than the two-bladed teetering rotor which is used by the UH-1D/H, the contractor calculated that the life cycle cost could be reduced by 10 percent by eliminating the requirement for a continuous trailing-edge spline. We do not feel that this is a good comparison for a fully articulated blade, and a greater reduction in life cycle cost could be attained.

During the course of the study, the contractor was hindered by a lack of engineering data on bolted and bonded composite joints. This was particularly true of allowable stress and fatigue data. This forced the contractor to take a very conservative design approach and resulted in higher life cycle cost. Further studies of bolted joints for rotor blade pocket attachment are currently being planned by this Directorate. An experimental program for a bonded replaceable rotor blade pocket is currently under way.

The program was conducted under the technical management of Philip J. Haselbauer, Structures Division, with engineering support from Joseph H. McGarvey, Reliability and Maintainability Division.

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SECTIONALIZED MAIN ROTOR BLADE
ADVANCED DESIGN STUDY

Final Report
D210-10293-1

By

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Prepared by

The Boeing Company, Vertol Division
Boeing Center
Philadelphia, Pennsylvania

for

IV

EUSTIS DIRECTORATE
U.S. ARMY AIR MOBILITY RESEARCH AND DEVELOPMENT LABORATORY
FORT EUSTIS, VIRGINIA

SUMMARY

This report covers a study undertaken for the advanced design of a sectionalized main rotor blade. The whole spectrum of the potential design arrangements was investigated, and a bolted-together design was selected and is presented as the preferable choice.

The structure of the chosen design is based on an aluminum-alloy extruded spar and an aluminum-alloy trailing-edge member with 18 fiberglass-reinforced-plastic (FRP) trailing-edge boxes attached to these components by machine screws. In order to avoid the effect of stress concentration in metal components, the concept of FRP-to-FRP bolted joints was used in highly stressed areas. This blade has been designed to provide the following features:

1. Components replaceable by an average Army helicopter mechanic
2. No special tools required at squadron-level maintenance activity
3. Component repair by sectionalized replacement on the helicopter
4. Capable of flight testing on the UH-1 helicopter

The complexities inherent with meeting all these design features dictated a substantial cost increase (approximately 50 percent) over the present UH-1H rotor blade. This cost increase, coupled with the contractual ground rules on inherent and external damage, provided the cost-analysis conclusion that the present UH-1H rotor blade is more economical based on a 10-year life-cycle cost criterion.

In determination of the value of this type of rotor blade for Army helicopters, additional studies are required to:

1. Determine the feasibility of applying this concept to a soft in-plane hingeless blade that eliminates the trailing-edge member or to an articulated blade designed for in-plane strength and stiffness without a continuous trailing edge.
2. Reevaluate the sectionalized blade with the incorporation of inherent damage analysis and human factors estimates of actual field operations.

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SECTION I

PROGRAM OBJECTIVE AND THE DEVELOPMENT OF ANALYTICAL TECHNIQUES

The program objective is to study the design of a helicopter blade capable of being flight-tested on a UH-1H helicopter and featuring components that can be replaced with the use of standard tools by an average U.S. Army mechanic without removing the blade from the aircraft.

STRESS ANALYSIS

A stress analysis was conducted in the conventional manner, using well-known formulas and techniques. In some cases where there was insufficient data (fiberglass-reinforced-plastic components), rational assumptions were made. In the analysis of blade dynamic properties, computer programs were used. Refer to Section III for the stress analysis summary.

MAINTENANCE CONCEPT

The maintenance concept defined for the individual blade concepts (present UH-1, proposed bonded, and proposed bolted) defines the organizational maintenance functions performed in meeting the requirements for an on-helicopter repairable rotor blade.

A reliability/maintainability evaluation of the sectionalized blade concepts developed during this program was made, with results as shown in Table I. The maintenance concept for UH-1 rotor blades is presented in Table II.

BLADE REPAIRABLE AND SCRAP DISTRIBUTION

The rotor blade damage summary provided as a data base for this program was plotted graphically (Figures 5 to 9) to provide a presentation of damage by types (puncture, dent, etc.) and by repair level (organizational or depot). Figures 1 to 4 are photographs of the types of external damage from which these graphs were developed.

TABLE I. RELIABILITY AND MAINTAINABILITY ANALYSIS

Parameter	Current UH-1	Bonded Box	Bolted Box				
			Baseline	No T.E.	No T.E. With Increased Spar	Without Replaceable L.E.	Without Replaceable Boxes
Cost of One Blade	$3,000*	$4,130	$4,800	$4,370	$4,480	$4,690	$4,600
Blade Spares Inventory	30% of Installed	None	None	None	None	None	None
MMH Field Repair		7.0	3.0	2.0	2.0	3.0	5.0
Part Matl Cost/Repair (Field)	$5.00	$5.00	$5.00	$5.00	$5.00	$5.00	$5.00
GSE, Tooling Cost/Repair (Field)	0	0	0	0	0	0	0
% Field Repair Requiring Removal	100	100	0	0	0	0	0
% Removed Blades Scrapped Org	30	37	37	37	65	40	55
% Removed Blades Repaired Org	12	63	N/A (63% on A/C)	N/A (63% on A/C)	N/A (35% on A/C)	N/A (60% on A/C)	N/A (45% on A/C)
% Removed Blades to Depot Repair	58	0	0	0	0	0	0
% Depot Received Blades Scrapped	68	N/A	N/A	N/A	N/A	N/A	N/A
% Depot Received Blades Overhaul	32	N/A	N/A	N/A	N/A	N/A	N/A
Blade Overhaul Cost, Depot	$925	N/A	N/A	N/A	N/A	N/A	N/A
Shipping Containers Required	30% of Installed	N/A	N/A	N/A	N/A	N/A	N/A

*Source: UH-1 and AH-1 Helicopter Main Rotor Blade Failure and Scrap Data Analysis, Bell Report No. 299-099-522 (Prepared under Contract DAAJ02-70-C-0016), Bell Helicopter Company, June 5, 1970.

TABLE II. MAINTENANCE CONCEPT FOR UH-1 BLADES

Damage	Current	Proposed Bonded	Proposed Bolted
SPAR			
Puncture (Any)	Scrap	Scrap	Scrap
Tear	Scrap	Scrap	Scrap
L.E. Erosion	Depot rework	Field replace erosion strip	Field replace erosion strip
Dents	Judgment (.005 in.)	Judgment	Judgment
Crack	Scrap	Scrap	Scrap
ROOT END DOUBLERS & GRIP PLATES			
Puncture	Scrap	Scrap	Scrap
Tear	Scrap	Scrap	Scrap
Dents	Judgment	Judgment	Judgment
TRAILING EDGE			
Puncture	Scrap	Field replace T.E.	Field replace T.E.
Tear	Scrap	Field replace T.E.	Field replace T.E.
Dents	Judgment	Judgment	Judgment
INTER-BOX TAPES			
All Discrepancies	N/A	Field replace tape	Field replace tape
BOX AREA			
Puncture	Repair circular damage less than 2.0 in. dia or less than 1.0 x 4.0 in. for oblong damage. Otherwise scrap.	Tape holes smaller than inter-rib spacing. Otherwise field replace box.	Field replace box for any damage. Repair of box as for bonded version is optional.
Tear	Do	Do	Do
Dent	Do	No action required if not punctured.	No action required if not punctured.
Scratch	Polish smooth. If skin becomes too thin, patch up to areas above.	Do	Do
Delamination	Repair for areas less than 30 sq in.	Field replace box	Field replace box
Entrapped Water	Scrap	N/A	N/A
INBOARD HONEYCOMB AREA			
Puncture	N/A	Field repair of honeycomb for areas up to 1 x 1 in. or 1½ in. dia.	Field repair of honeycomb for areas up to 1 x 1 in. or 1½ in. dia.
Tear	N/A	Do	Do
Dent	N/A	Do	Do
Delamination	N/A	Field repair of honeycomb for areas up to 2 sq. in.	Field repair of honeycomb for areas up to 2 sq. in.
Entrapped Water	N/A	Scrap	Scrap

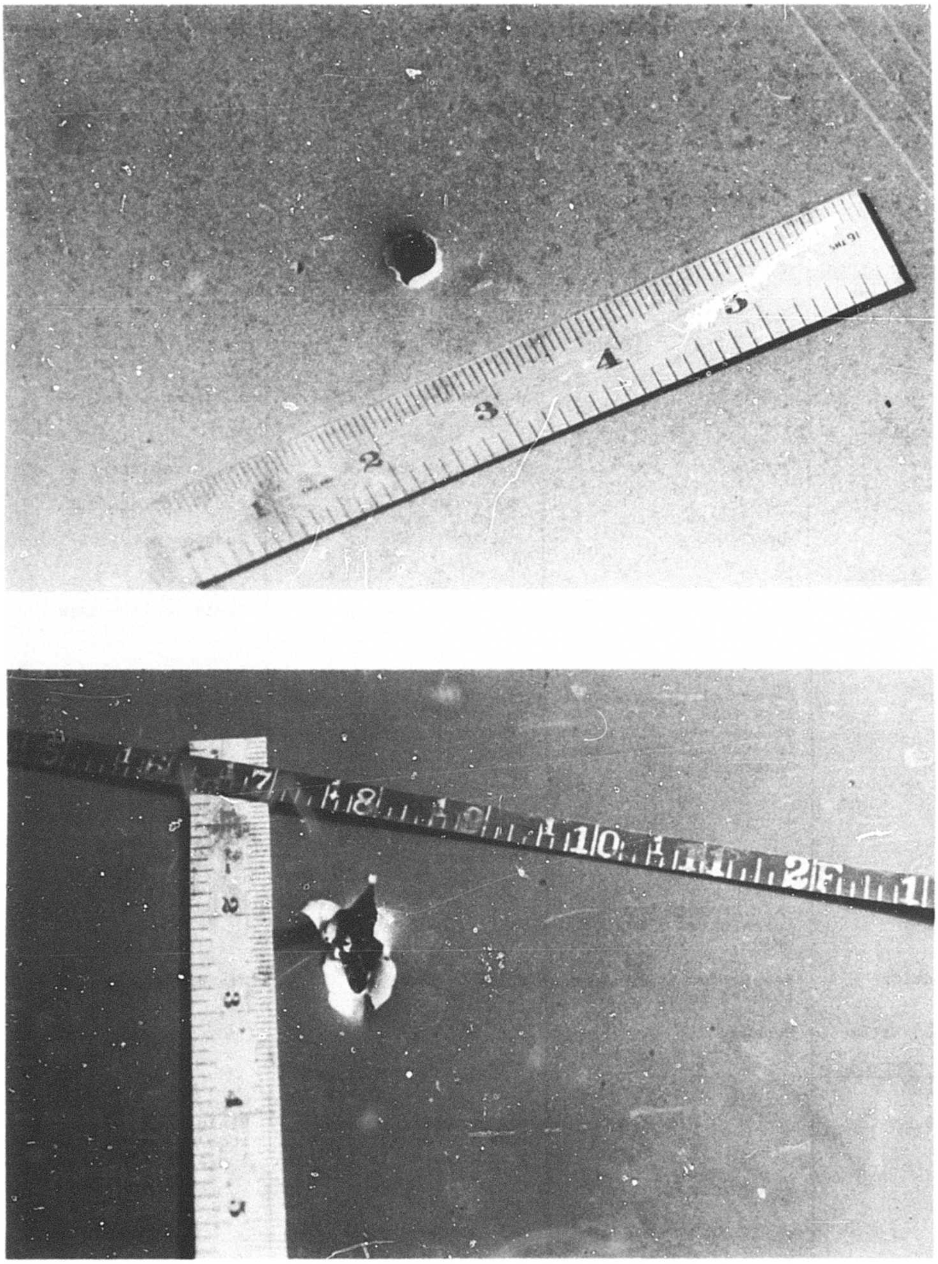

Figure 1. Typical UH-1 Blade Damage Used in Analysis - Bullet Holes.

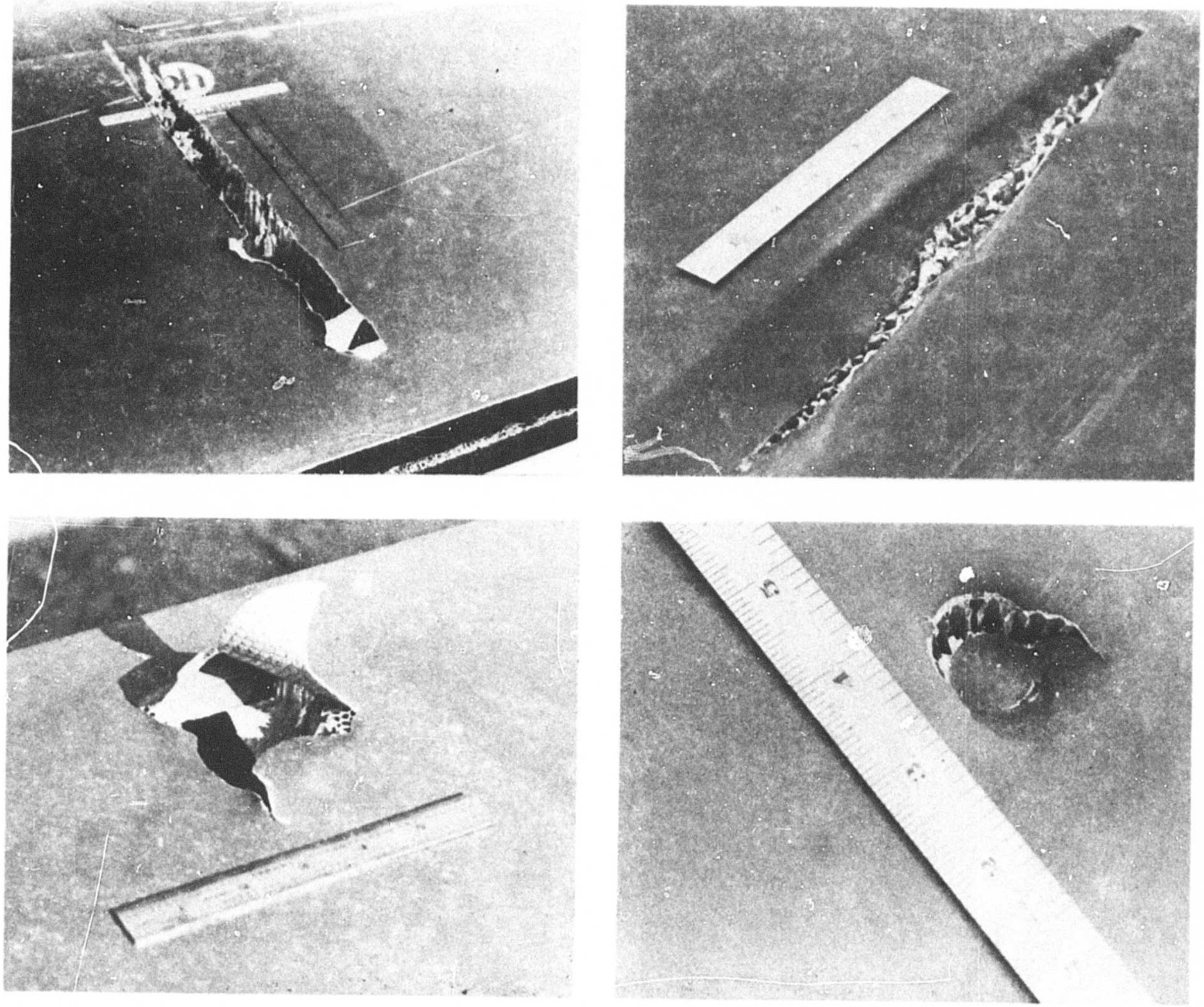

Figure 2. Typical UH-1 Blade Damage Used in Analysis - Tears or Gashes.

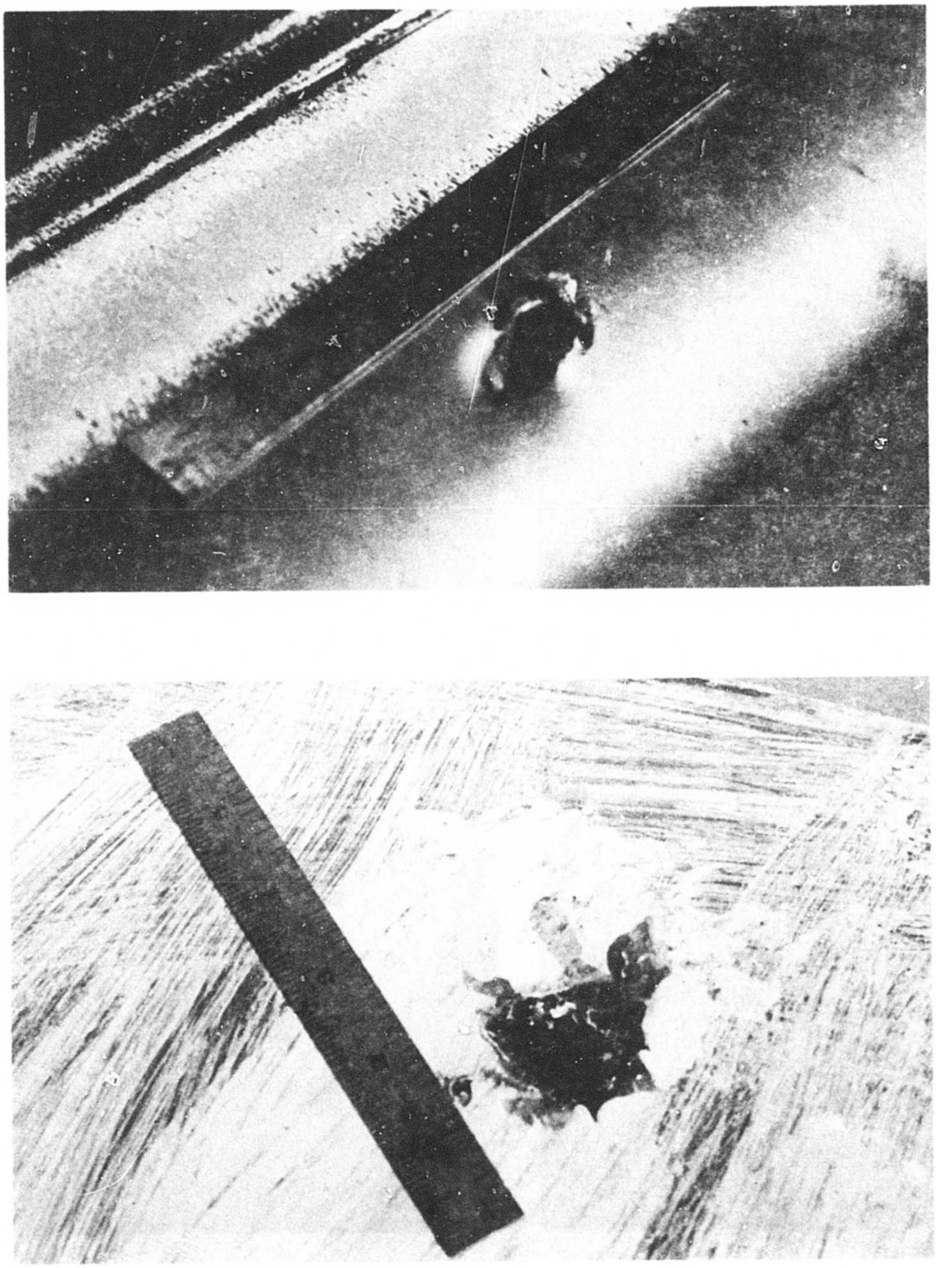

Figure 3. Typical UH-1 Blade Damage Used in Analysis - Punctures.

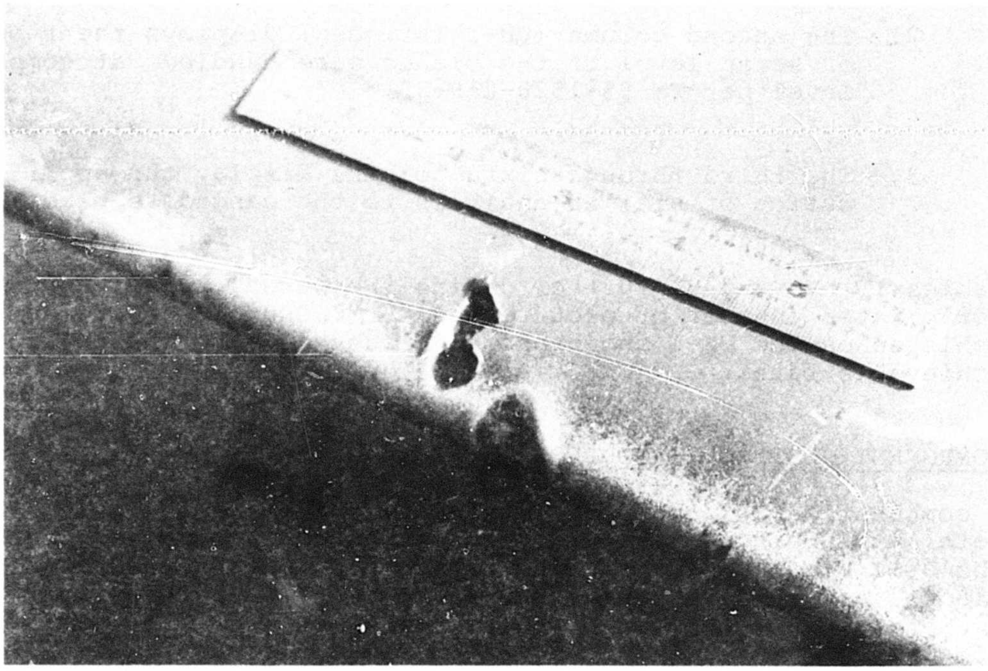

Figure 4. Typical UH-1 Blade Damage Used in Analysis - Dent.

Table III presents the distribution of the damage criteria in the following manner:

1. The first column (UH-1 Actual) defines the selection of organizational and depot repair or scrap to meet the percentage distribution from the statement of work.

2. The second column (UH-1 Intended) displays the repair or scrap level if the blades were handled at company level per TM 55-1520-219-35.

3. The third through sixth columns display the application of similar analysis to the candidate blades.

Tables IV, V, and VI further define the actual repair and scrap rates (number of occurrences per 1,000 hours) presently achieved on the UH-1 and proposed blades and the theoretically achievable rates.

COMPONENT COSTING METHODOLOGY

A combination of detail standard data, historical costing data, and Boeing-Vertol pricing structures was applied to both the Bell blade design and the various concepts of sectionalized blades, as generated by Boeing-Vertol Design Engineering.

In addition, several quotes were solicited from vendors in specific areas.

Where applicable, detail prices were extracted from the Government price list as furnished by the Department of the Army.

The indicated prices are not to be considered as a firm price quotation from Boeing-Vertol. The price numbers may be used in relative price analyses only.

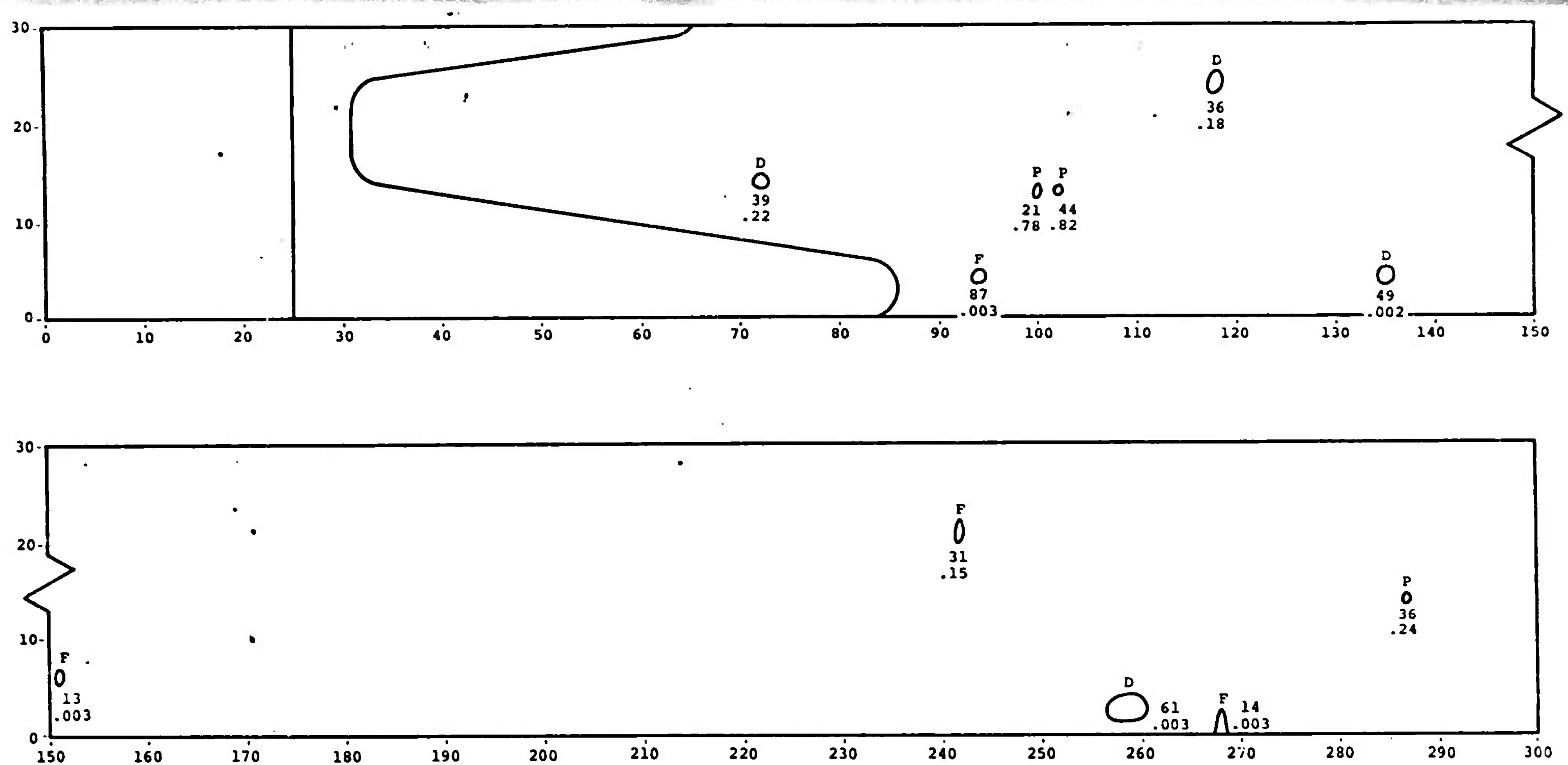

Figure 5. Organizational Repair.

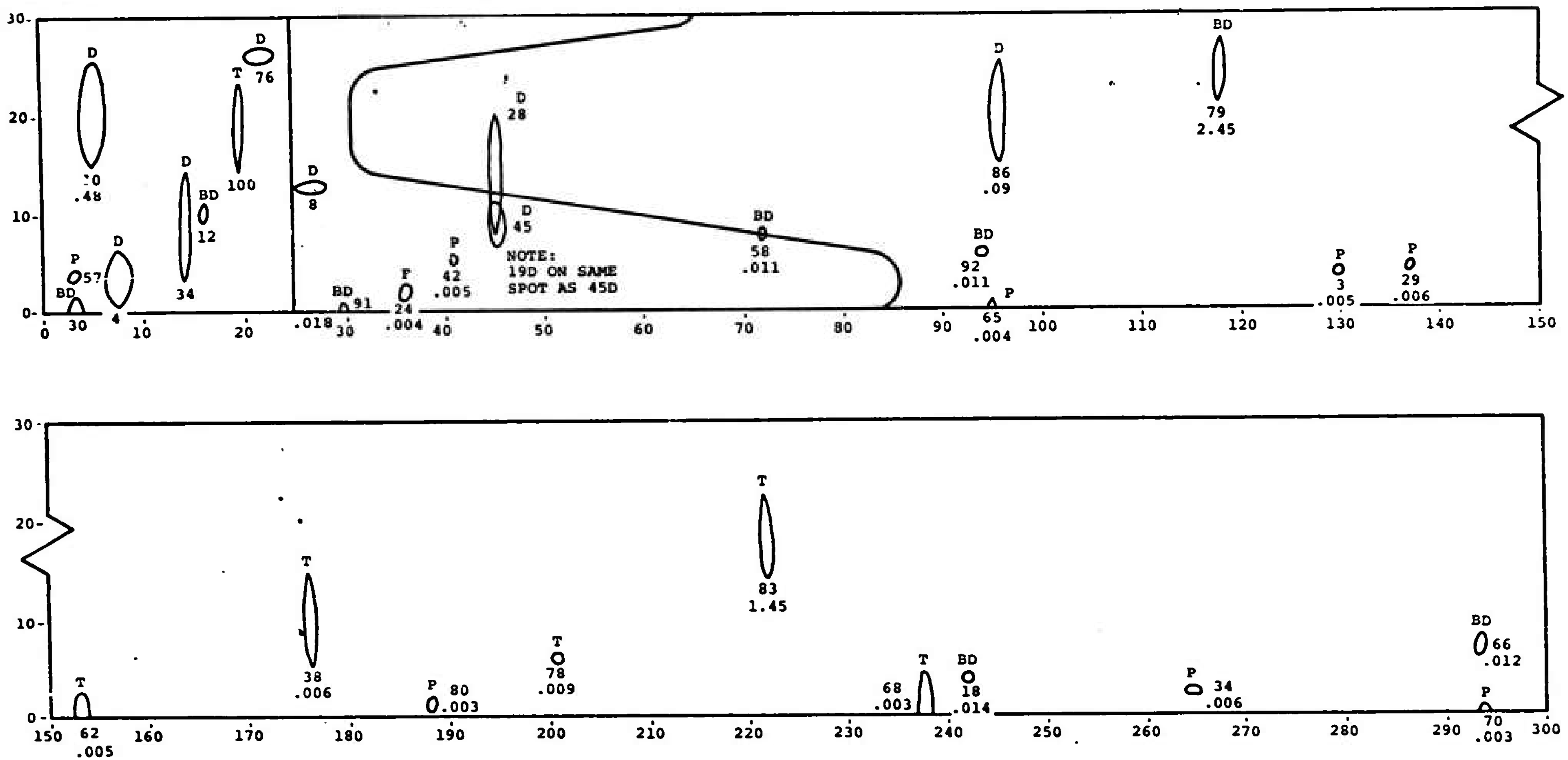

Figure 6. Organizational Scrap.

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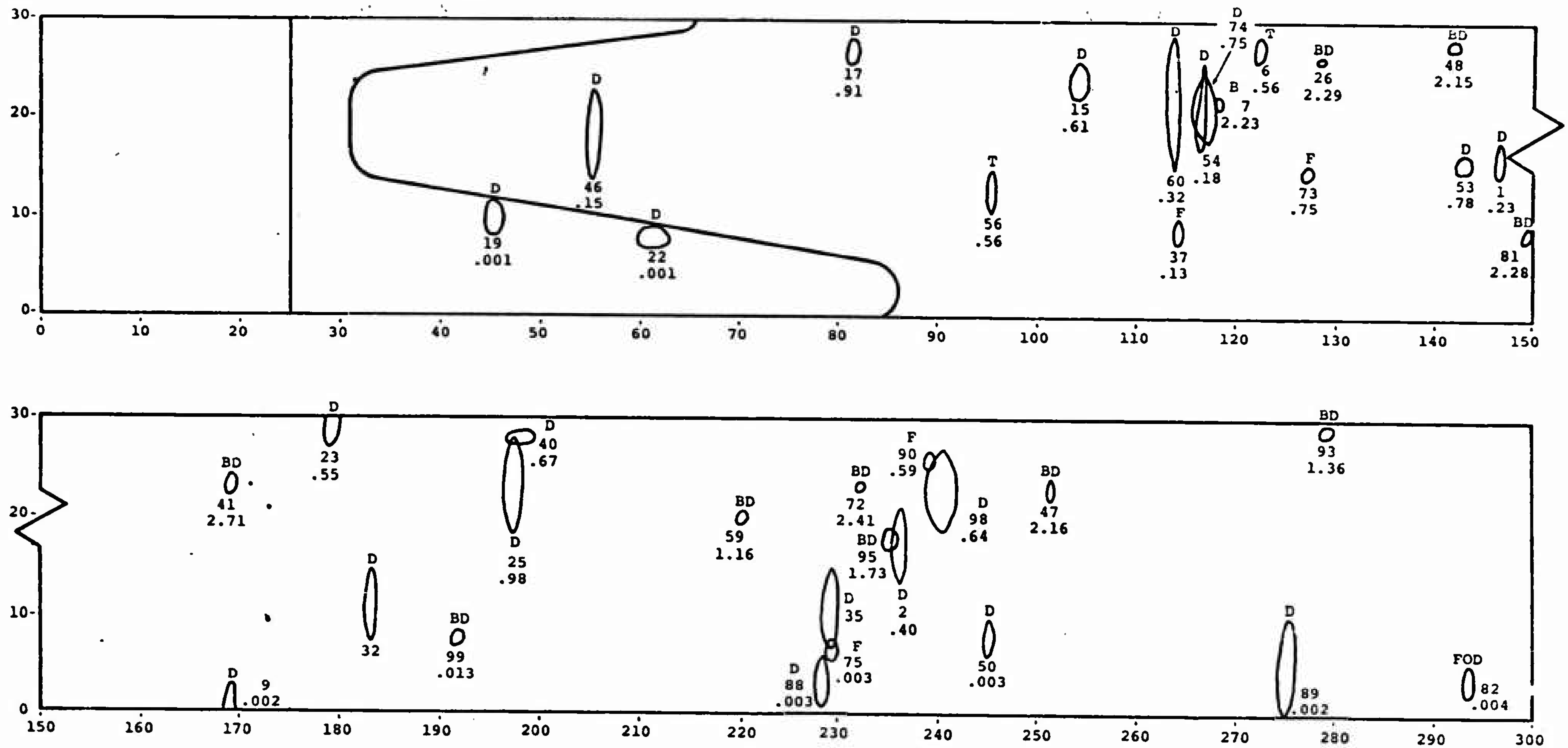

Figure 7. Depot Scrap.

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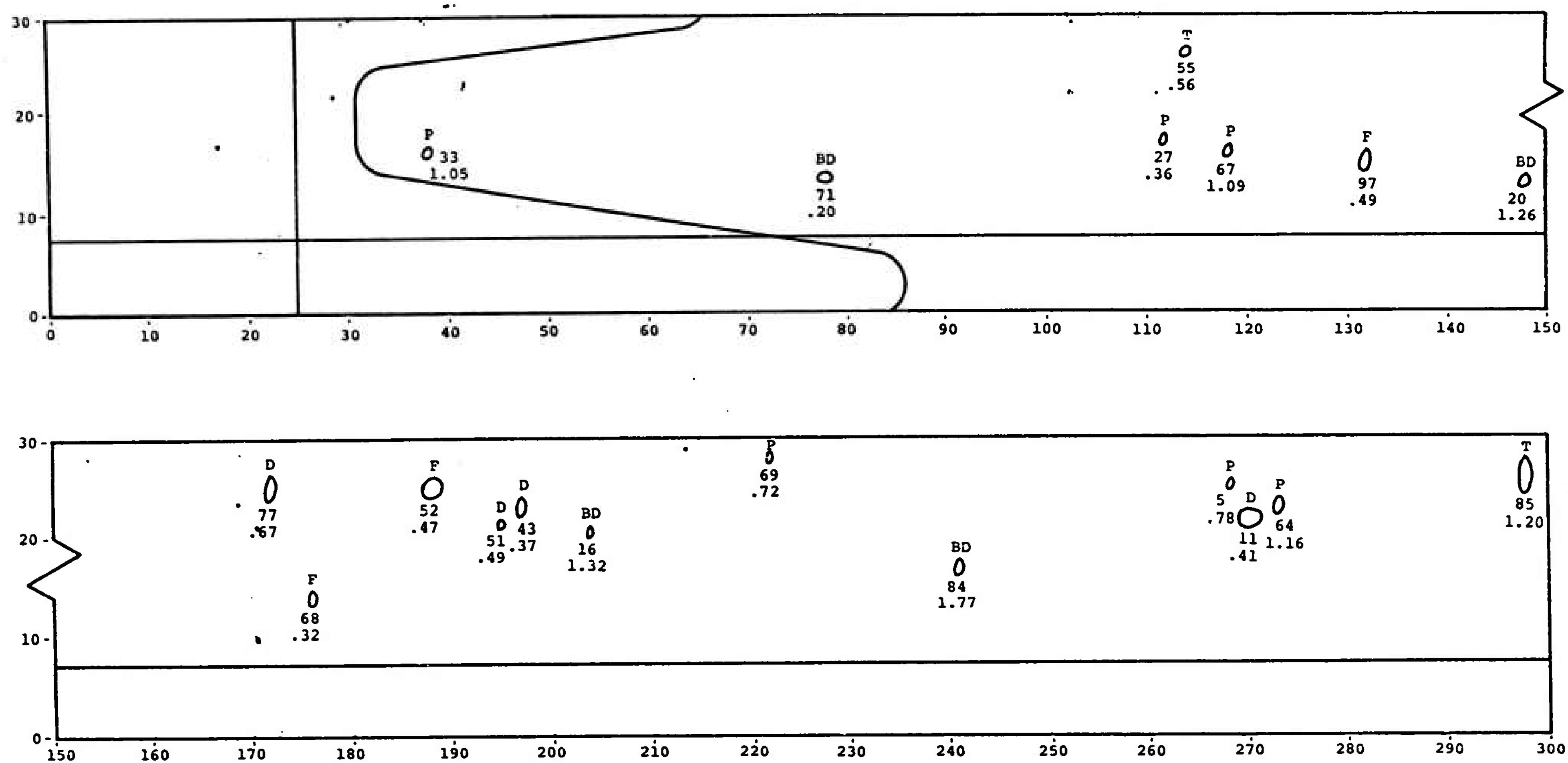

Figure 8. Depot Repair.

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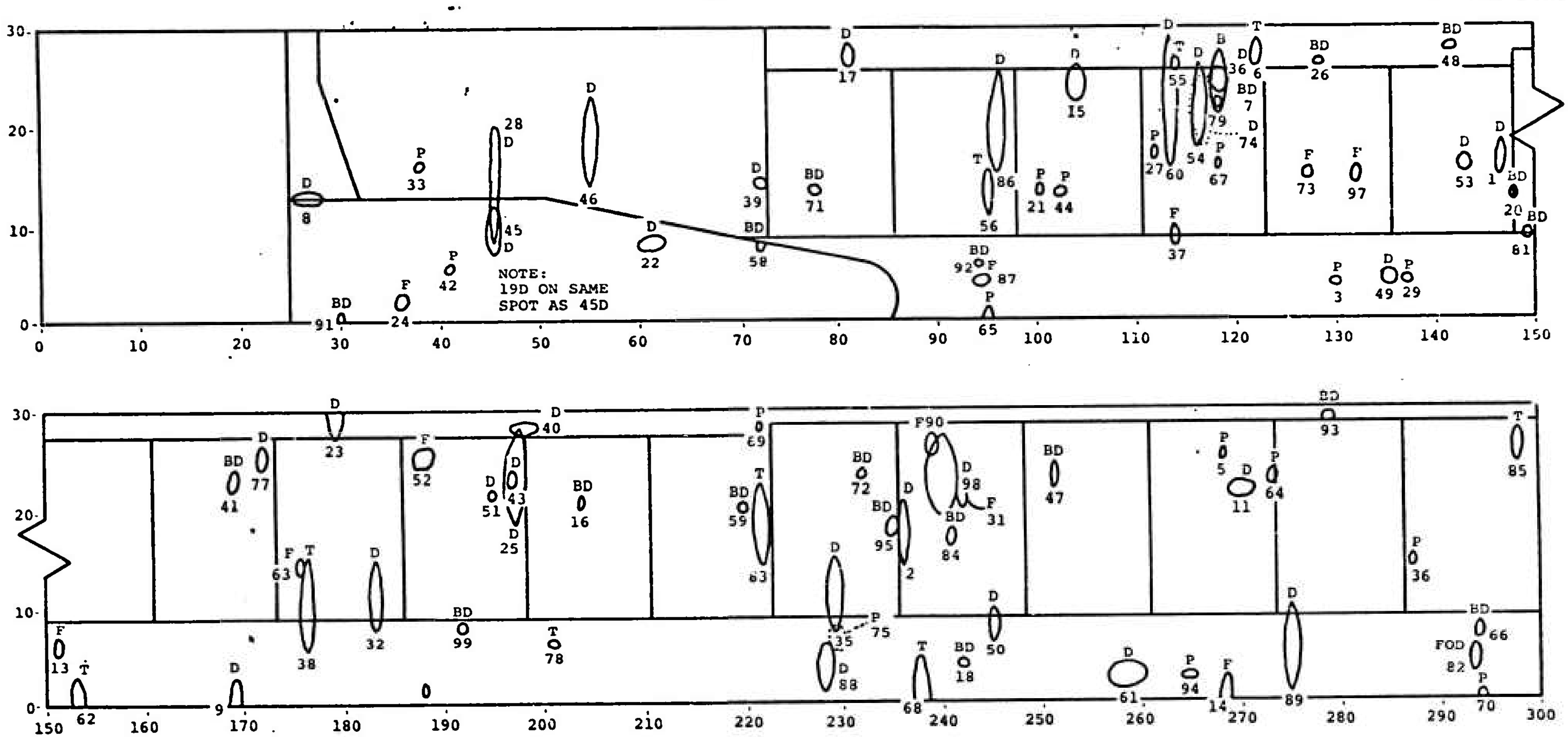

NOTE - SAME PLANFORM FOR BOLTED AND BONDED BLADES

Figure 9. Field Repairable Blade.

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TABLE III. BLADE REPAIRABLE AND SCRAP DISTRIBUTION

Damage Incident Number	Current UH-1 Blade								Bonded Field Repairable Blade								Bolted Field Repairable Blade							
	Actual				Intended				Actual				Intended				Actual				Intended			
	Org		Depot		Org		Depot		Org		Depot		Org		Depot		Org		Depot		Org		Depot	
	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S
1				x		x			x				x				x				x			
2				x		x			x				x				x				x			
3		x				x				x				x				x				x		
4											Hub Damaged													
5			x		x				x				x				x				x			
6				x		x					x		x				x				x			
7				x		x			x				x				x				x			
8		x				x				x				x				x				x		
9				x		x						x		x						x		x		
10											Hub Damaged													
11			x		x				x				x				x				x			
12											Hub Damaged													
13	x				x				x				x				x				x			
14	x				x				x				x				x				x			
15				x		x					x		x				x				x			
16			x		x				x				x				x				x			
17				x		x					x		x				x				x			
18		x				x				x				x				x				x		
19				x		x						x		x						x		x		
20			x		x				x				x				x				x			
21	x				x				x				x				x				x			
22				x		x						x		x						x		x		
23				x		x					x		x				x				x			
24		x				x				x				x				x				x		
25				x		x					x		x				x				x			
26				x		x					x		x				x				x			
27			x		x				x				x				x				x			
28		x				x				x				x				x				x		
29		x				x				x				x				x				x		
30											Hub Damaged													
31	x				x				x				x				x				x			
32				x		x						x		x						x		x		
33			x		x						x		x						x		x			
34											Hub Damaged													
35				x		x						x		x						x		x		
36	x				x				x				x				x				x			
37				x		x						x		x						x		x		
38		x				x				x				x				x				x		
39	x				x						x		x						x		x			
40				x		x					x		x				x				x			
41				x		x			x				x				x				x			
42		x				x				x				x				x				x		
43			x		x				x				x				x				x			
44	x				x				x				x				x				x			
45		x				x				x				x				x				x		
46				x		x				x				x				x				x		
47				x		x			x				x				x				x			
48				x		x					x		x				x				x			
49	x				x				x				x				x				x			
50				x		x						x		x						x		x		

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TABLE III - Continued																								
	Current UH-1 Blade								Bonded Field Repairable Blade								Bolted Field Repairable Blade							
	Actual				Intended				Actual				Intended				Actual				Intended			
Damage Incident Number	Org		Depot		Org		Depot		Org		Depot		Org		Depot		Org		Depot		Org		Depot	
	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S
51			x		x				x				x		x						x			
52			x		x				x				x		x						x			
53				x		x			x				x		x						x			
54				x		x					x		x		x						x			
55			x		x						x		x		x						x			
56				x		x			x				x		x						x			
57												Hub Damaged												
58		x				x				x				x		x						x		
59				x		x			x				x		x						x			
60				x		x					x		x		x						x			
61	x				x				x				x		x						x			
62		x				x				x				x		x						x		
63			x		x				x				x		x						x			
64			x		x				x				x		x						x			
65		x				x				x				x		x						x		
66		x				x				x				x		x						x		
67			x		x				x				x		x						x			
68		x				x				x				x		x						x		
69			x		x						x		x		x						x			
70		x				x				x				x		x						x		
71			x		x				x				x		x						x			
72				x		x			x				x		x						x			
73				x		x			x				x		x						x			
74				x		x			x				x		x						x			
75				x		x						x		x				x		x		x		
76												Hub Damaged												
77			x		x								x		x						x			
78		x				x				x				x		x						x		
79		x				x					x		x		x						x			
80		x				x				x				x		x						x		
81				x		x				x				x		x						x		
82				x		x						x		x		x		x		x		x		
83		x				x			x				x		x						x			
84			x		x				x				x		x						x			
85			x		x				x				x		x						x			
86		x				x			x				x		x						x			
87	x				x				x				x		x						x			
88				x		x						x		x		x		x		x		x		
89				x		x						x		x		x		x		x		x		
90				x		x			x				x		x						x			
91		x				x				x				x		x						x		
92		x				x				x				x		x						x		
93				x		x					x		x		x						x			
94		x				x				x				x		x						x		
95				x		x			x				x		x						x			
96	x				x				x				x		x						x			
97			x		x				x				x		x						x			
98				x		x			x				x		x						x			
99				x		x						x		x		x		x		x		x		
100												Hub Damaged												

TABLE III - Continued																								
Damage Incident Number	Current UH-1 Blade								Bonded Field Repairable Blade								Bolted Field Repairable Blade							
	Actual				Intended				Actual				Intended				Actual				Intended			
	Org		Depot		Org		Depot		Org		Depot		Org		Depot		Org		Depot		Org		Depot	
	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S	R	S
Totals	11	23	19	39	30	62	0	0	42	22	16	12	58	34	0	0	56	22	2	12	58	34	0	0
%	12.0	25.0	20.7	42.3	32.6	67.4	-	-	45.7	23.9	17.4	13.0	63.0	37.0	-	-	60.9	23.9	2.2	13.0	63.0	37.0	-	-
% Repair Org	12.0				32.6				45.7				63.0				60.9				63.0			
% Repair Depot	20.7				-				17.4				-				2.2				-			
% Repair Total	32.7				32.6				63.1				63.0				63.1				63.0			

Alternate Bolted Box Configurations

Damage Summary	No T.E.	No T.E. Increased Spar	Without Replaceable L.E.	Without Replaceable Box
% Repair Org	63.0	35.0	60.0	45.0
% Repair Depot	0	0	0	0
% Repair Total	63.0	35.0	60.0	45.0

TABLE IV. CURRENT MAINTENANCE PRACTICE (REPAIR)												
Blade Config.	Current				Bonded				Bolted			
Maint Level	Org Repair		Depot Repair		Org Repair		Depot Repair		Org Repair		Depot Repair	
Damage	#	Rate	#	Rate	#	Rate	#	Rate	#	Rate	#	Rate
Spar												
Puncture	-	-	-	-	-	-	-	-	-	-	-	-
Tear	-	-	-	-	-	-	-	-	-	-	-	-
L.E. Erosion, FOD	3	32.6	-	-	3	32.6	-	-	3	32.6	-	-
Dents	2	21.7	-	-	2	21.7	-	-	2	21.7	-	-
Doublers and Grip Plate												
Puncture	-	-	-	-	-	-	-	-	-	-	-	-
Dents	-	-	-	-	-	-	-	-	-	-	-	-
FOD	-	-	-	-	-	-	-	-	-	-	-	-
Trailing Edge												
Puncture	-	-	1	10.9	-	-	5	54.4	5	54.4	-	-
Tear	-	-	1	10.9	-	-	2	21.7	2	21.7	-	-
Dents	-	-	-	-	-	-	7	76.1	7	76.1	-	-
Inboard Honey-comb Area												
Puncture	-	-	1	10.9	-	-	1	10.6	-	-	1	10.9
Dents	1	10.9	-	-	-	-	1	10.9	-	-	1	10.9
Box Area												
Puncture	3	32.6	8	87.0	17	184.8	-	-	17	184.8	-	-
Tear	-	-	1	10.9	3	32.6	-	-	3	32.6	-	-
Dent	1	10.9	4	43.5	10	108.7	1	10.9	11	119.6	-	-
FOD	1	10.9	3	32.6	6	65.2	-	-	6	65.2	-	-
Totals	11	119.6	19	206.7	41	445.6	17	184.9	56	608.7	2	21.8

TABLE V. CURRENT MAINTENANCE PRACTICE (SCRAP)

Blade Config.	Current				Bonded				Bolted			
Maint Level	Org		Depot		Org		Depot		Org		Depot	
	Scrap		Scrap		Scrap		Scrap		Scrap		Scrap	
Damage	#	Rate	#	Rate	#	Rate	#	Rate	#	Rate	#	Rate
Spar												
Puncture	9	97.8	2	21.7	10	108.7	1	10.9	10	108.7	1	10.9
Tear	4	43.5	-	-	4	43.5	-	-	4	43.5	-	-
L.E. Erosion, FOD	-	-	3	32.6	-	-	3	32.6	-	-	3	32.6
Dents	-	-	6	65.2	-	-	6	65.2	-	-	6	65.2
Doublers and Grip Plate												
Puncture	3	32.6	-	-	3	32.6	-	-	3	32.6	-	-
Dents	3	32.6	2	21.7	3	32.6	2	21.7	3	32.6	2	21.7
FOD	1	10.9	-	-	1	10.9	-	-	1	10.9	-	-
Trailing Edge												
Puncture	1	10.9	3	32.6	-	-	-	-	-	-	-	-
Tear	-	-	1	10.9	-	-	-	-	-	-	-	-
Dents	-	-	7	76.1	-	-	-	-	-	-	-	-
Inboard Honeycomb Area												
Puncture	-	-	-	-	-	-	-	-	-	-	-	-
Dent	-	-	1	10.9	1	10.9	-	-	1	10.9	-	-
Box Area												
Puncture	-	-	6	65.2	-	-	-	-	-	-	-	-
Tear	1	10.9	1	10.9	-	-	-	-	-	-	-	-
Dent	1	10.9	5	54.4	-	-	-	-	-	-	-	-
FOD	-	-	2	21.7	-	-	-	-	-	-	-	-
Totals	23	250.1	39	423.9	22	239.2	12	130.4	22	239.2	12	130.4

TABLE VI. INTENDED MAINTENANCE PRACTICE (SCRAP AND REPAIR)												
Blade Config.	Current				Bonded				Bolted			
Maint Level	Org				Org				Org			
	Repair		Scrap		Repair		Scrap		Repair		Scrap	
Damage	#	Rate	#	Rate	#	Rate	#	Rate	#	Rate	#	Rate
<u>Spar</u>												
Puncture	-	-	11	119.6	-	-	11	119.6	-	-	11	119.6
Tear	-	-	4	43.5	-	-	4	43.5	-	-	4	43.5
L.E. Erosion, FOD	3	32.6	3	32.6	3	32.6	3	32.6	3	32.6	3	32.6
Dents	2	21.7	6	65.2	2	21.7	6	65.2	2	21.7	6	65.2
<u>Doublers and Grip Plate</u>												
Puncture	-	-	3	32.6	-	-	3	32.6	-	-	3	32.6
Dents	-	-	5	54.4	-	-	5	54.4	-	-	5	54.4
FOD	-	-	1	10.9	-	-	1	10.9	-	-	1	10.9
<u>Trailing Edge</u>												
Puncture	1	10.9	4	43.5	5	54.4	-	-	5	54.4	-	-
Tear	1	10.9	1	10.9	2	21.7	-	-	2	21.7	-	-
Dents	-	-	7	76.1	7	76.1	-	-	7	76.1	-	-
<u>Inboard Honeycomb Area</u>												
Puncture	1	10.9	-	-	1	10.9	-	-	1	10.9	-	-
Dent	1	10.9	1	10.9	1	10.9	1	10.9	1	10.9	1	10.9
<u>Box Area</u>												
Puncture	11	119.6	6	65.2	17	184.8	-	-	17	184.8	-	-
Tear	1	10.9	2	21.7	3	32.6	-	-	3	32.6	-	-
Dent	5	54.4	6	65.2	11	119.6	-	-	11	119.6	-	-
FOD	4	43.5	2	21.7	6	65.2	-	-	6	65.2	-	-
Totals	30	326.1	62	673.9	58	630.5	34	369.6	58	630.5	34	369.6

LOGISTICS ANALYSIS

Optimum Repair Level Analysis (ORLA)

Simulation model ORLA is a fully developed working tool which has been used by Boeing-Seattle for approximately 18 months and recently became available to Vertol Division of the Boeing Company. The model will be used in this program to assist in weighing the various factors which must be considered in the design of an expendable rotor blade. This model defines the principal factors or variables and their interrelationships which determine the life-cycle costs that would be incurred from each of three different repair level concepts.

1. Discard-at-failure-maintenance (DAFM)

2. Repair-at-failure-maintenance (RAFM), where repair is accomplished at the direct support level

3. RAFM, where the repair is accomplished at the depot level

Figure 10 shows the inputs and their relationship to the model. Table VII presents the repair time analysis used in the cost model.

There are three principal outputs from this model:

1. Cost of DAFM

2. Cost of RAFM where the repair is accomplished at the direct support level

3. Cost of RAFM where the repair is accomplished at the depot level

Logistics Analysis Summary

Table VIII presents a summary of the cost comparisons for the blades evaluated. (Figure 11 details the MTBR versus blade cost requirements for a bolted or bonded blade configuration.)

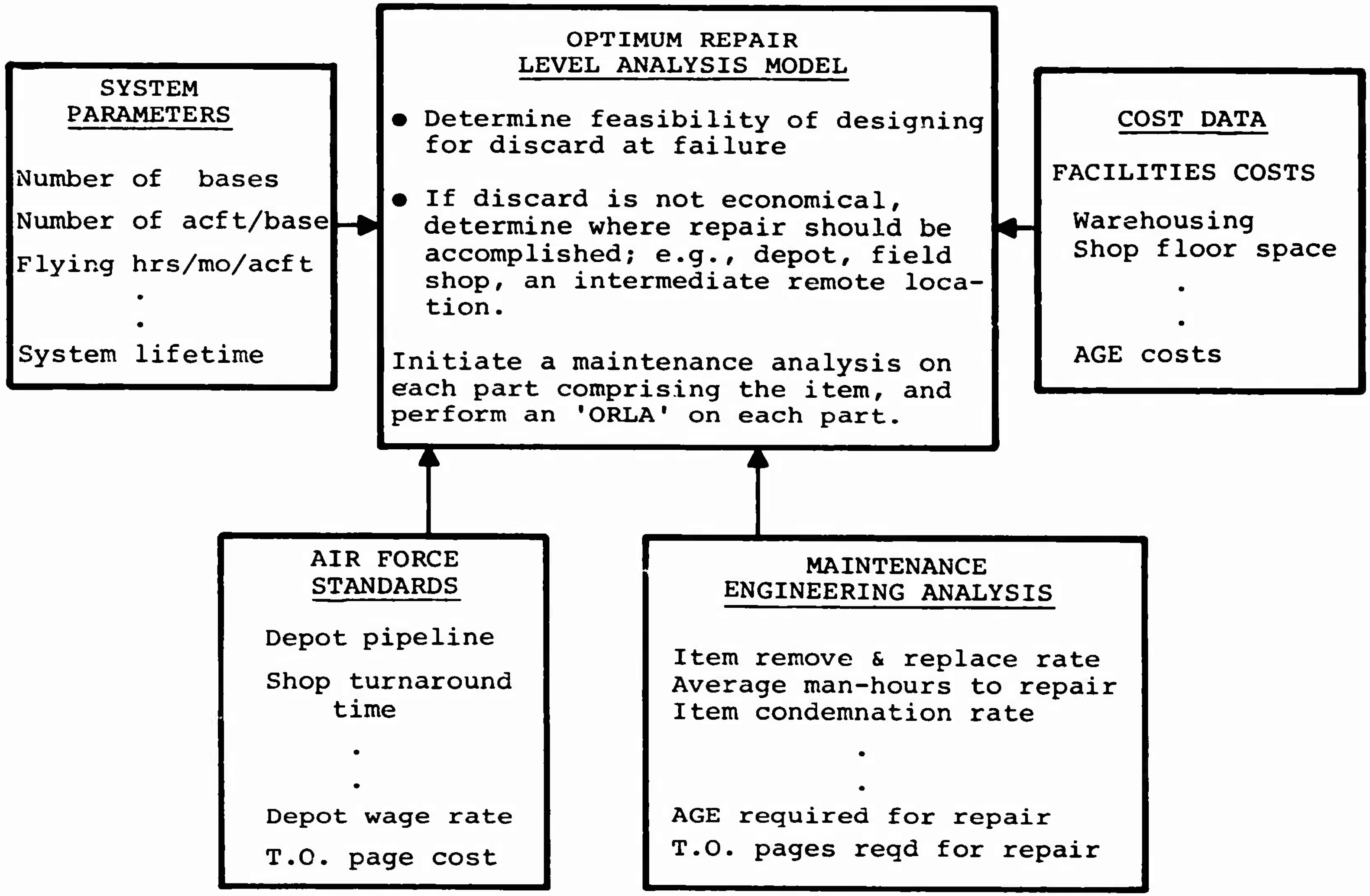


Figure 10. Optimum Repair Level Analysis (ORLA).

TABLE VII. REPAIR TIME ANALYSIS OF UH-1 FIELD REPAIRABLE BLADE

Component		Time (Min) Bonded	Bolted
Spar			
Puncture - Nonrepairable		-	-
Battle Damage - Nonrepairable		-	-
Tear - Nonrepairable		-	-
L.E. Erosion, FOD -			
Outer Blade			
Remove 12 screws at 1/2 min ea	6 min	53	53
Remove and inspect gang nut strip	1		
Dress spar mating surface	2		
Install new erosion strip - 12 screws	6		
Shape 12 screw heads @ 1-1/2 min ea	18		
Base time (obtain part, arrive at job)	20		
Inner Blade			
Polish out nicks, apply finish, 1 min ea	1	21	21
Base time	20	21	21
Dents - Same as L.E. Erosion		21	21
Doublers and Grip Plate			
Puncture - Nonrepairable		-	-
Dents - Nonrepairable		-	-
FOD - Nonrepairable		-	-

Component		Time (Min) Bonded	Bolted
<u>Trailing Edge</u>			
Puncture (Bonded T.E.)		210	
Detach damage T.E.	120 min		
Dress mating surface	30		
Apply new bonding adhesive	10		
Install new T.E. and clamp	10		
Remove clamps, dress and paint	20		
Base time	20		
Puncture (Bolted T.E.)			76
Remove 90 bolts - 1/2 min ea	23 min		
Clean box T.E. slots	5		
Install 90 bolts - 1/4 min ea	23		
Paint	5		
Base time	20		
Tear - Same as Puncture			76
Dents - Same as Puncture			76
<u>Inboard Honeycomb Area</u>			
Puncture		44	44
Holesaw away old skin and core	15 min		
Apply bonding agent to core	2		
Insert plug and fair	5		
Apply skin patch	2		
Base time	20		

TABLE VII - Continued

Component		Time (Min) Bonded	Bolted
Dents - Same as Puncture		44	44
<u>Box Area</u>			
Puncture (holes smaller than 2.0 in. dia or 1.0 x 4.0 in.)		28	28
Smooth area around hole and clean	2 min		
Cut out tape shape	1/2		
Apply tape	1/2		
Paint	5		
Base time	20		
<u>Bonded T.E. Version</u>		65*	
Puncture (holes larger than 2.0 in. (dia or 1.0 x 4.0 in.)			
Cut away major box sections	5 min		
Chip away bonded areas	5		
Remove tapes	1		
Clean and dress 3 bonding areas	5		
Apply bonding agents	1		
Position and clamp replacement box	2		
Remove clamps	-		
Apply inter-box tapes	1		
Paint	5		
Base time (before and after bonding)	10		

TABLE VII - Continued			
Component		Time (Min)	
		Bonded	Bolted
Bolted T.E. Version			46*
Puncture (Holes Larger than 2.0 dia. or 1.0 x 4.0)			
Remove 19 screws	9-1/2 Min		
Remove tapes	1		
Remove old box	-		
Dress mating surfaces	1		
Insert new box and 19 screws	9-1/2		
Paint	5		
Base time	20		
Dents and FOD - Same as for large punctures (small dents and FOD will go unrepaired or simply filled)			

*Add 5 minutes if box replacements necessitate disturbing L.E. strip.

NOTE: Maintenance Man-hours for Field Repair - The maintenance manhours for field repair used in the economic analysis are an average of the times to perform the various tasks (replace box, replace L.E., etc.) as required by the damage size and location. The times used are adjusted from ideal time lines to reflect a combat non-Conus environment.

TABLE VIII. REPAIR CONCEPT COST COMPARISON		
Blade Type	Field Repair Cost	Field Discard Cost
UH-1	$11,546,130	$11,877,390
Bonded	6,951,997	16,081,220
Bolted		
• Baseline	7,539,683	17,920,080
• No Trailing Edge	7,327,862	16,320,400
• Increased Spar; No Trailing Edge	11,663,150	16,729,620
• No Replaceable Leading Edge	8,295,001	17,510,860
• No Replaceable Boxes	10,868,420	17,176,040

NOTE: Depot repair costs are not presented since all configurations are field scrappable.

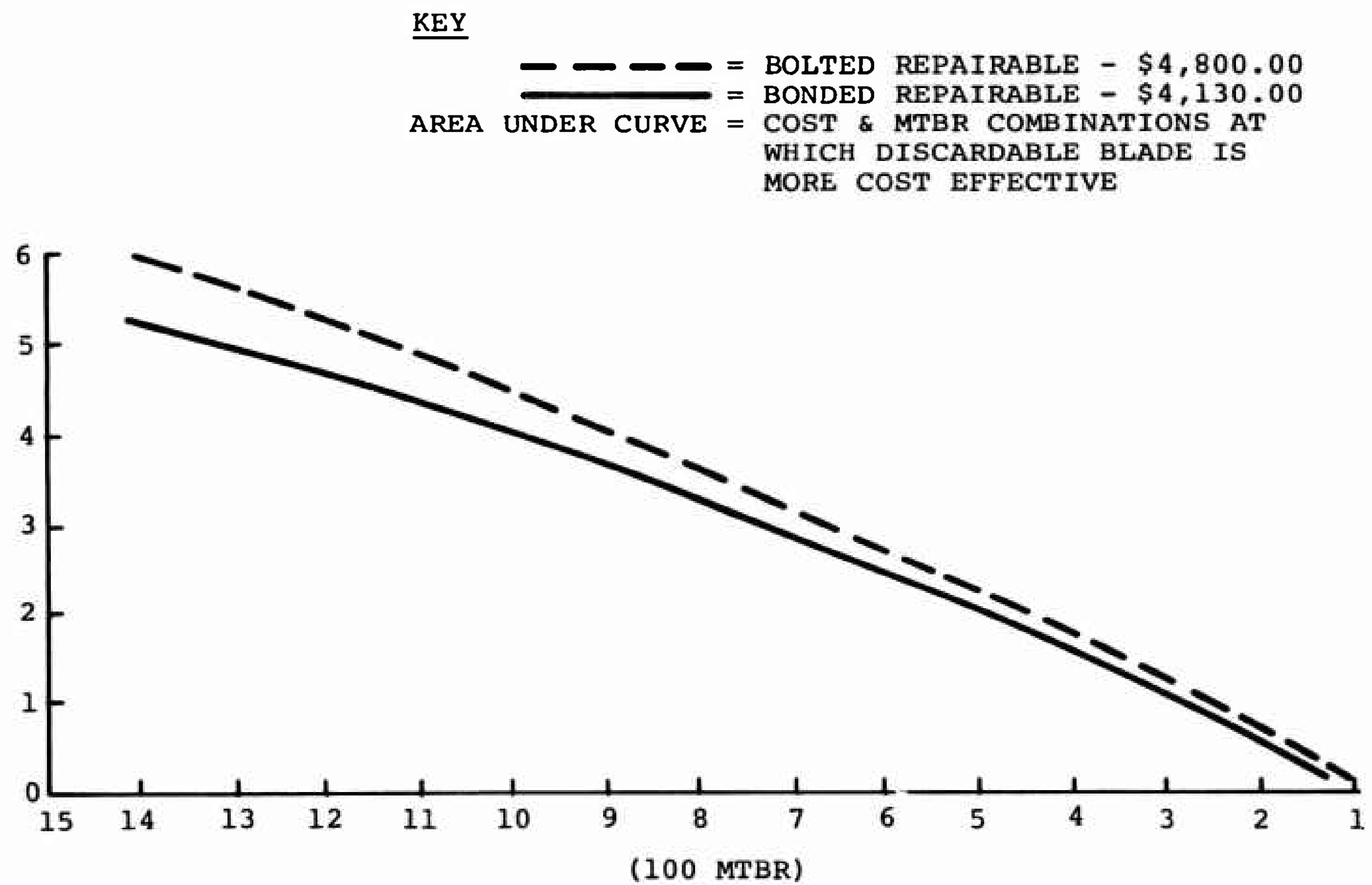


Figure 11. Rotor Blade Logistics (Based on 10-Year Life Cycle Costs).

SECTION II

DESIGN ARRANGEMENTS CONSIDERED IN THE STUDY

The design of a helicopter blade is a particularly difficult task due to the variety of requirements imposed by aerodynamic, dynamic, stress, weight, reliability, service, maintenance, and cost specifications. Safety is the paramount factor in helicopter utilization, and consequently, when designing a helicopter blade, every effort is made to eliminate discontinuities, holes, notches, and the like which introduce structurally detrimental stress-concentration factors. The concept of unitized blade design evolved to satisfy this requirement. This concept is represented in metal blade designs by Bell (aluminum alloy) and Lockheed (stainless steel) blades and in fiber-reinforced blades by the Boeing-Vertol family of glass- and boron-reinforced blades. These blades are nearly free from stress concentrations, but they have one common characteristic: difficulty in making blade repairs and associated high maintenance costs.

This drawback led to the sectionalized blade concept which would feature easily replaceable components. The incorporation of the concept of a sectionalized blade in the form of flyable hardware is not a simple task. If the only tool required to replace the damaged blade component were a screwdriver (highly desirable), the blade would contain numerous discontinuities (holes) for bolted connections. Their presence in a metal blade design (sheet, extrusion, or rolled stock) would introduce numerous stress concentration factors leading to low fatigue life or increased blade weight.

With the use of composites as blade structural material, the presence of the holes is less objectionable, since fibrous materials are less sensitive to stress concentration factors than crystalline structure materials like metals. Consequently, it is intended to use fiberglass-reinforced plastic (FRP) components wherever alternating stress levels prevent the use of metal joints.

REVIEW OF PREVIOUS DESIGNS

The survey of technical literature and the review of past attempts to design and manufacture the sectionalized blade included three major cases:

- American: Kaman Aircraft Corporation, K-17 Cold Pressure Vehicle, and UH-2 Utility Helicopter.
- British: Rotorway Ltd., "Helicopter Rotor Blade Development", Ministry of Technology Contract KK/191/032/CB25(a). (See Figure 12.)
- Russian: MIL 6 and 10 rotor blade, described in Canadian Aeronautics and Space Journal, April 1968, by Dr. A.V. Nekrassov. (See Figure 13.)

In 1955, Kaman designed and developed their K-17 Cold Pressure Jet Helicopter Research Vehicle. The rotor blade design embraced interchangeable trailing-edge segments fastened to the spar by flush-head bolts. In this design, the bolt hole pierces material extending from the spar aft edge. This vehicle was successfully flight tested in 1958. This interchangeable trailing-edge segment concept was used in the development of the UH-2 helicopter.

Kaman's UH-2 blade consisted of an extruded aluminum-alloy spar and FRP trailing-edge boxes attached to the spar lugs by six (three upper and three lower) flush head bolts. The widely spaced attachment bolts did not prevent the deflection of the box trailing edge under airloads, creating airflow disturbance and aerodynamic losses. More importantly, during flight testing of the UH-2, the need for increased inplane stiffness became evident. This increased stiffness was accomplished by wrapping the blades with additional fiberglass skins and trailing-edge doublers which effectively converted the blade to a unitized structure.

Redesign of the blade to revert to the sectionalized configuration by increasing the chord depth of the basic spar and stiffening the bolted connection were not attempted. Consequently, Kaman's sectionalized blade concept is not used in the production of UH-2 blades.

Rotorway's approach was based on the concept of a sandwich spar structure consisting of two stainless steel skins with resin-impregnated asbestos molded between them and trailing-edge boxes bolted to the spar. In order to reduce the adverse effect of bolted attachment on the life of the blade, a series of holes was drilled through a flange located in the plane of symmetry of the blade section. Consequently, flap bending had a very small effect on stresses in the joint, but lead-lag bending still created peak stresses around bolt holes and failures occurred at these locations during bench tests.

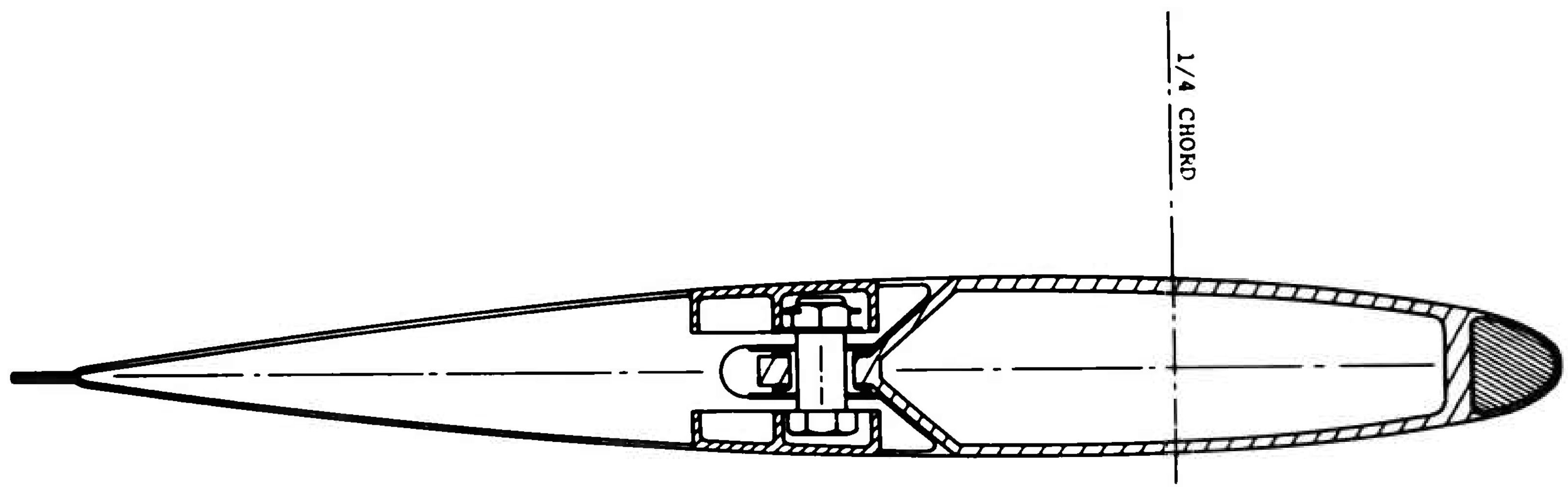


Figure 12. Rotorway Sectionalized Blade (English).

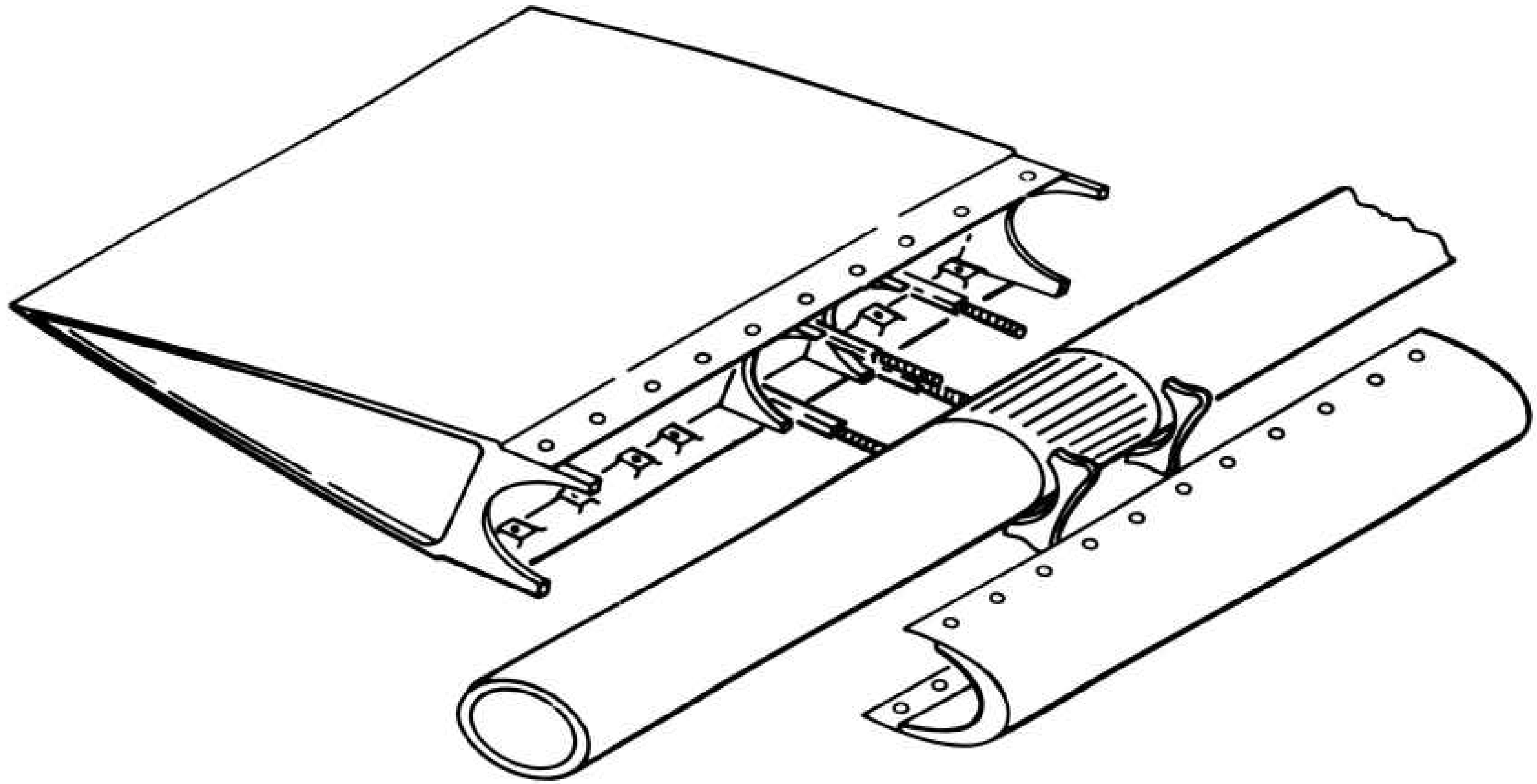


Figure 13. MIL-6 Helicopter Sectionalized Blade (Russian).

The Russian concept is based on an oval-cross-section steel spar completely free from mechanical discontinuities, holes, etc. Blade segments are attached to the spar by means of bond and bands. These segments are not simply trailing-edge boxes extending aft of the spar; they are composed of leading-edge and trailing-edge portions joined together by means of bond and a series of small bolts. The Russian concept yields a blade which is rather flexible in the plane of rotation (there is no trailing-edge member), and for this reason it was not considered as a potential application in this study.

REVIEW OF PROPOSED DESIGN ARRANGEMENTS

Minimum-Change Blade (See Figure 14)

This solution offers a design which may be converted into hardware with minimum time and expenditure due to the fact that the main structural member (spar) is retained as is, along with the leading-edge hardware. The inboard-end laminations undergo minor reshaping. Completely new elements are the trailing-edge boxes and trailing-edge member.

All-Fiberglass-Reinforced-Plastic (FRP) Blade (See Figure 15)

As a completely new design, this concept offers considerable freedom in selecting blade parameters as long as the required blade dynamic characteristics are maintained. For instance, the width of the blade spar and the position of its front edge may be determined in such a way that the installation of the removable leading-edge portion is practical. This was not possible with the minimum-change blade. The all-FRP blade may present a problem in matching its dynamic properties with those of the UH-1H blade. Changes in blade geometry may become necessary.

Four-Component Spar Blade (See Figure 16)

This concept seeks to achieve the greatest possibility of replacement of individual blade components. The solution, however, becomes too complex when its practicability is thoroughly investigated. The pitch of assembly bolts, determined by shear flow, becomes rather small (approximately 1.5 inches). Several hundred bolts would have to be removed and reinstalled in replacing a damaged top or bottom spar panel. The concept was abandoned.

Wraparound Steel Spar Blade (See Figure 17)

The main objective in this design was to obtain the maximum redundancy offered by two-spar solutions. The main problem was forming the spar. Cryogenic forming of stainless-steel tubing was considered as most promising in this application.

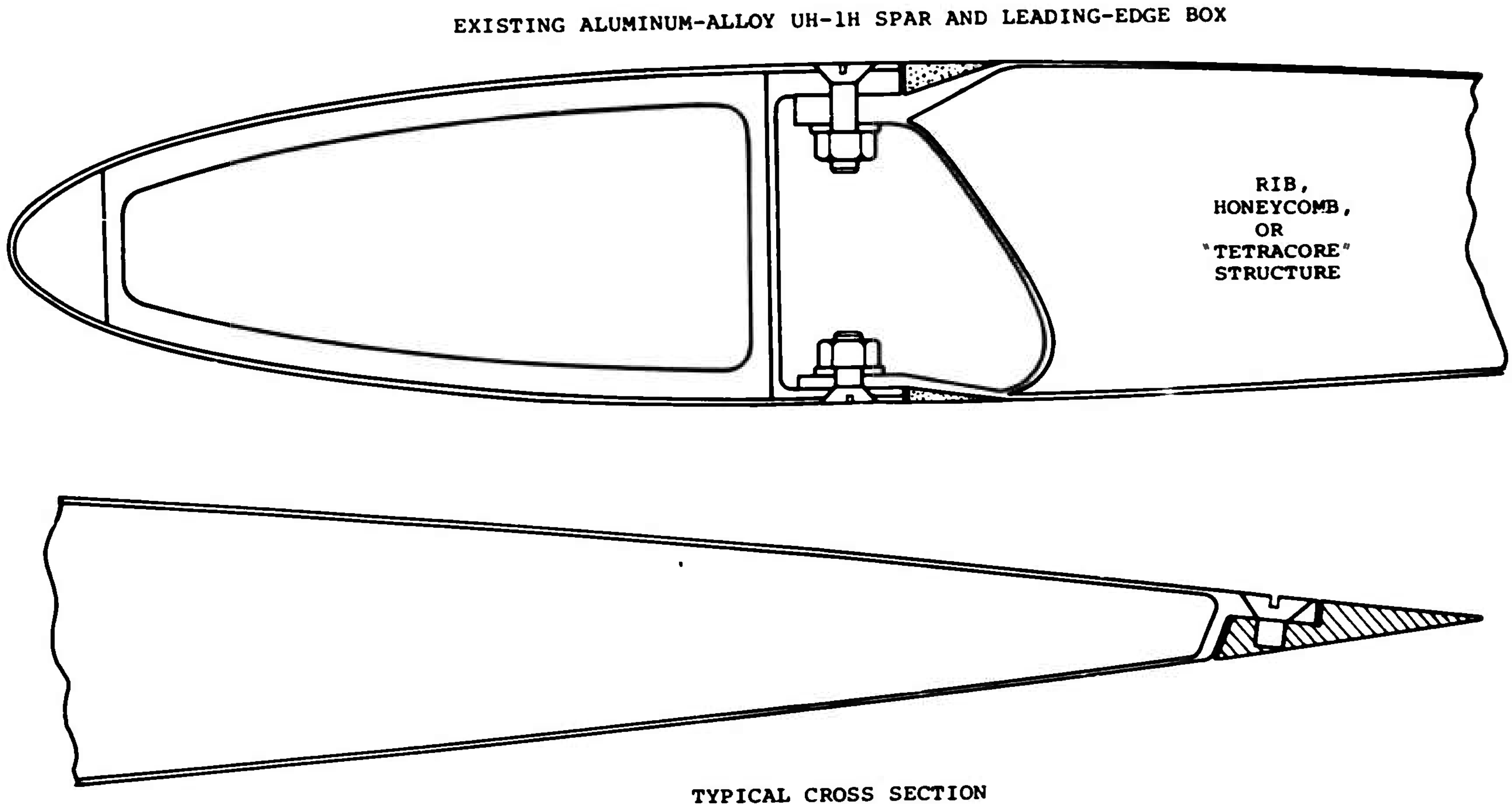


Figure 14. Minimum Change Blade.

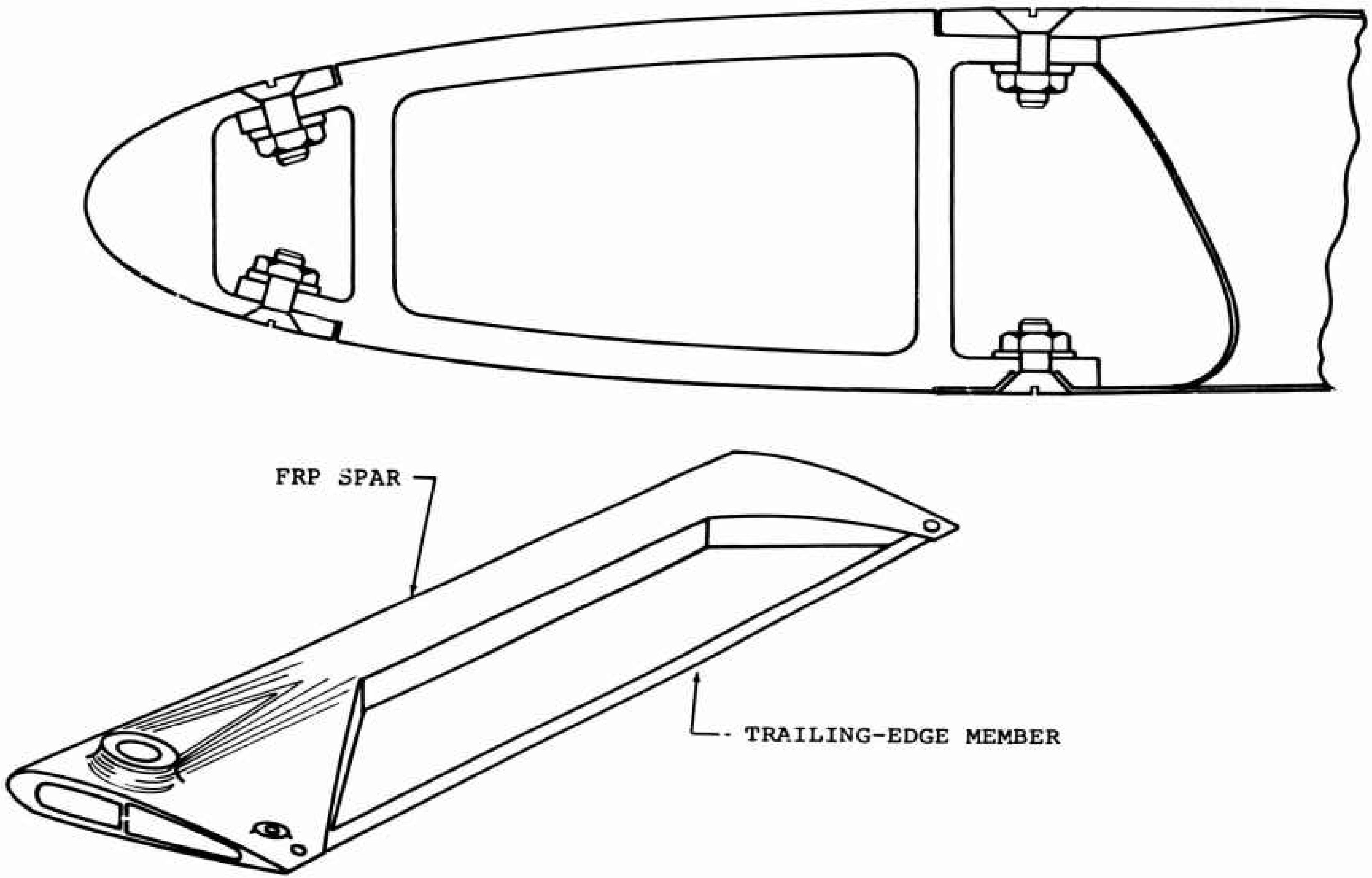


Figure 15. All Fiberglass-Reinforced-Plastic (FRP) Blade.

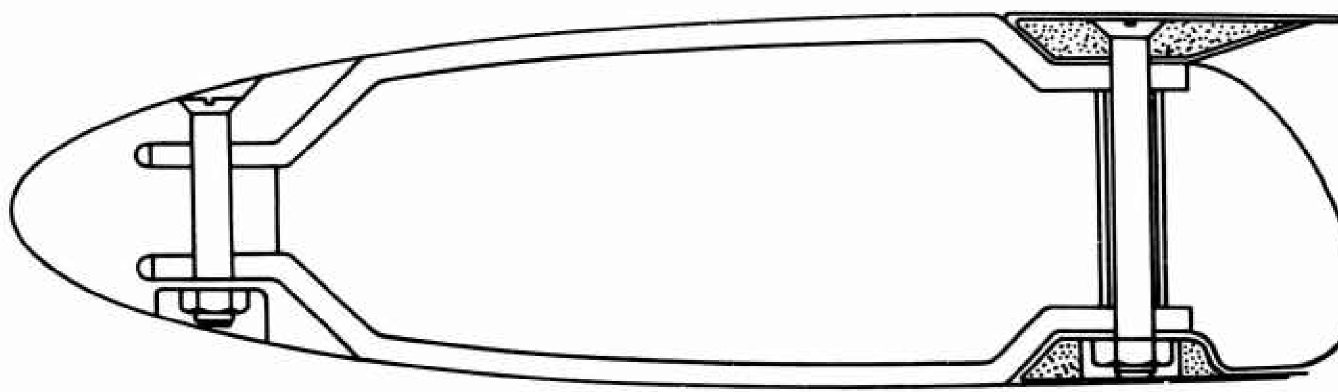


Figure 16. Four-Component Spar Blade.

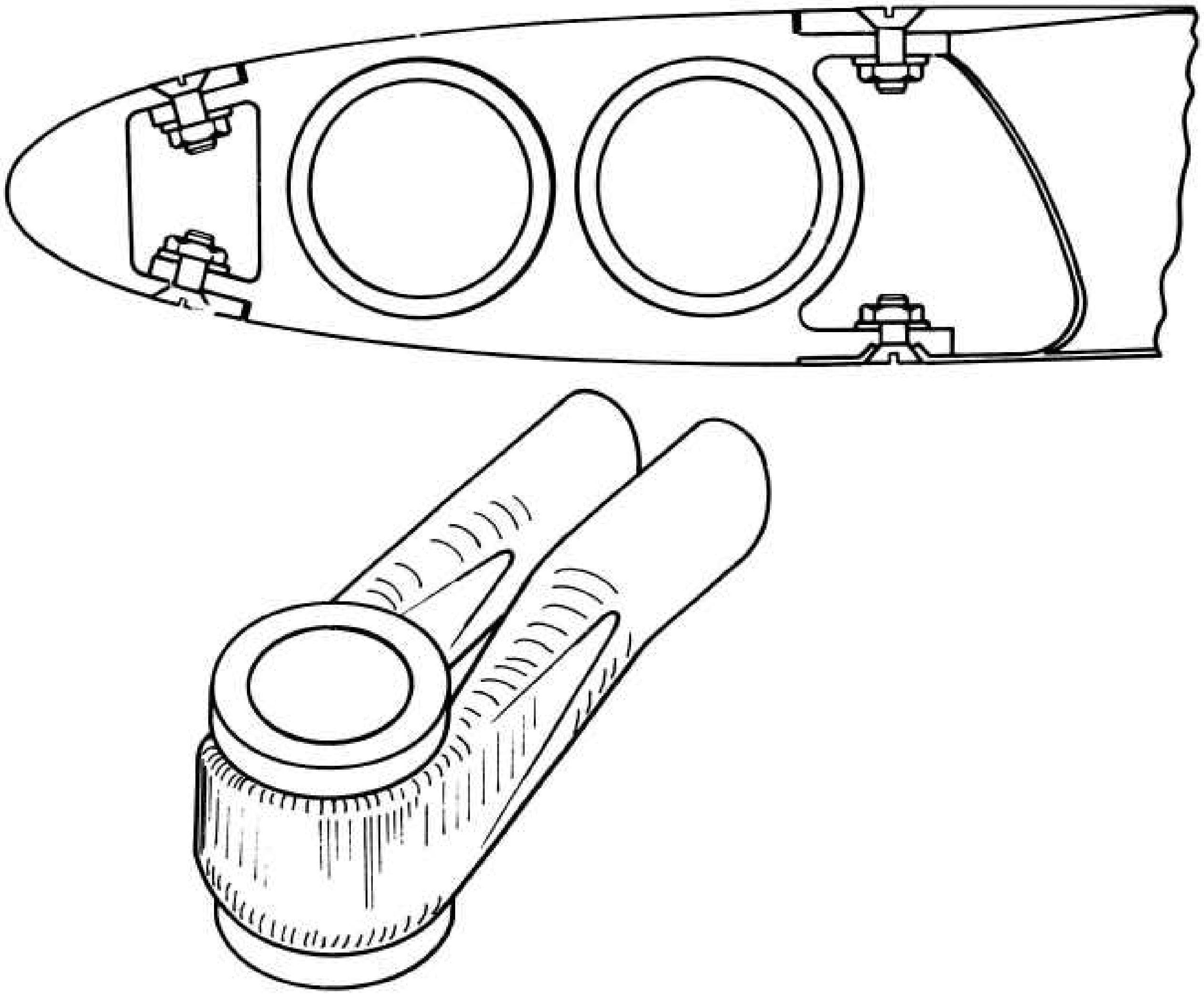


Figure 17. Wraparound Steel Spar Blade.

Although such facilities are already available and in use, further investigation revealed that the initial length of the spar tube (over 45 feet) makes the concept impractical with presently available facilities.

DETAIL REVIEW OF MINIMUM-CHANGE BLADE AND ALL-FRP BLADE

Minimum-Change Blade

The minimum-change blade, when subjected to a more detailed stress analysis, proved to be an unacceptable solution due to the effect on stiffness around all three axes (as compared with the UH-1H blade).

The replacement of the UH-1H blade's aft portion of continuous aluminum-alloy skin by short boxes of FRP structure substantially modified the blade characteristics. Blade torsional and in-plane properties were measurably affected. In order to restore the blade frequencies currently inherent to the UH-1H blade, it was necessary to increase the width of the spar extrusion. Thus the minimum-change blade evolved into a blade featuring a spar extrusion with a rear web located at 28.6 percent of chord instead of at 25.7 percent as shown on Figures 18 and 19. This design arrangement becomes the basic design which will be discussed thoroughly in a subsequent section of this report.

A blade design solution eliminating the trailing-edge was also taken into consideration (Figure 20). However, this blade does not meet the requirement of inplane stiffness and therefore cannot be flown on the UH-1H helicopter. In order to meet the stiffness requirement, the width of the spar should be increased to 60 percent of the chord. However, this would increase the blade weight beyond an acceptable limit since it would be almost double the weight of the typical section. Consequently, for this study the soft inplane sectionalized blade was considered for purposes of comparison only (see Table VIII).

The relatively small reduction in the procurement cost of the sectionalized blade without the trailing-edge spline (in comparison to the cost of the proposed blade shown in Figure 18) is explained by the fact that the trailing-edge boxes constitute the largest portion of the total blade cost. (See Table VIII.)

All-FRP Blade

An all-FRP structure for the sectionalized blade seemed to be attractive due to its relatively low sensitivity to stress concentration factors (holes, notches, etc.) as compared with aluminum-alloy structure.

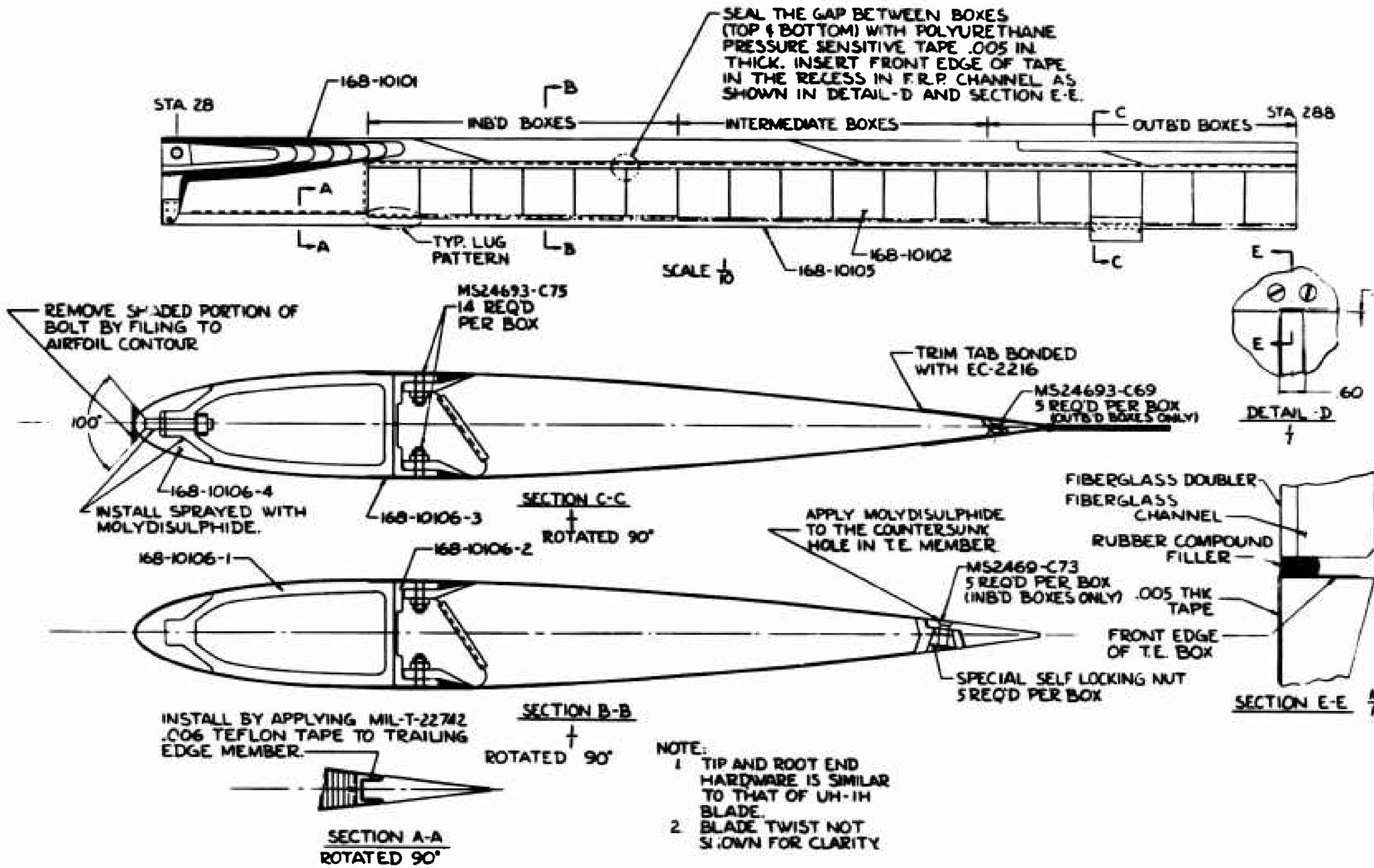


Figure 18. Bolted Sectionalized Blade Assembly.

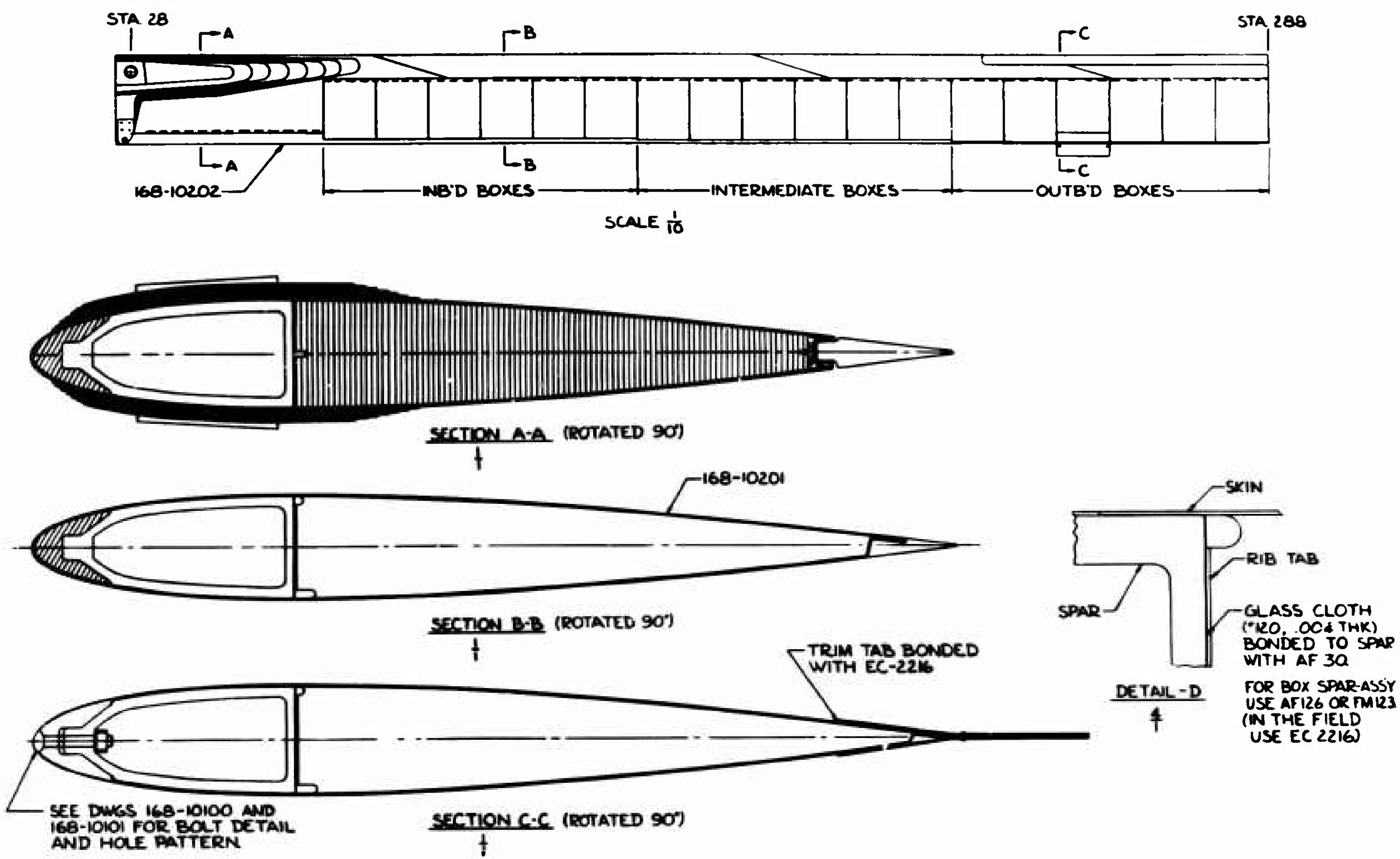


Figure 19. Bonded Secticnalized Blade Assembly.

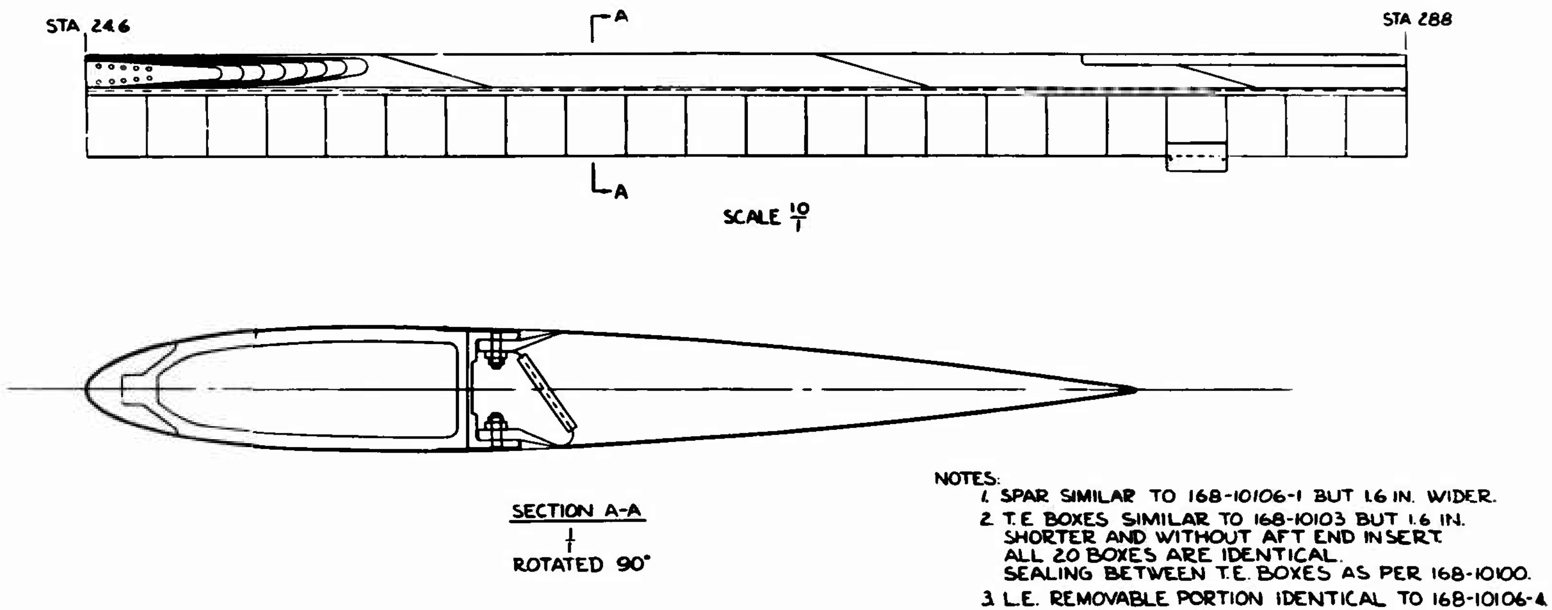


Figure 20. Soft Inplane Sectionalized Blade.

A thorough investigation of the possibility of using FRP in application to the sectionalized blade revealed two problem areas.

The first is of a general nature: The relatively low modulus of elasticity of FRP makes it impossible to match the dynamic properties of the blade when a change from aluminum alloy to FRP is made. This problem could be overcome if high-modulus fibers were used, or if significant changes in blade geometry were allowed (taper in planform and airfoil thickness).

The first solution is not recommended at the present time due to the relatively high cost of structural material. The second solution involves a developmental risk due to the requirement that the blade be capable of being flight-tested on a UH-1H aircraft. In this case significant changes in blade geometry would not be acceptable.

The second problem area lies in the root-end attachment. As in every FRP structure, the transfer of large, concentrated loads presents a difficult task due to the relatively low shear and bearing allowables of composites. An attachment featuring a bolt-and-hole solution is considered impractical due to limited edge distance of the main attachment pin and the limited total thickness of the blade in the root-end area. These conditions would result in unacceptable shear tearout stresses of the FRP.

One solution which eliminates the problem of low shear allowable is a wraparound configuration in which the high tensile properties of FRP may be efficiently used. A wraparound root-end attachment was considered for the sectionalized blade for the UH-1H helicopter until loads data from a UH-1H flight survey revealed high maneuver peak moments which would create load-reversal conditions in the root-end area. Under this condition the advantages of the wraparound attachment disappear.

The installation of some kind of clamping device, such as that used on the Messerschmitt-Boelkow-Blohm BO-105, would solve the problem of load reversal. Such a solution is not practical for the UH-1H sectionalized blade because of space limitations of the present hub configuration.

The root-end attachment problem, coupled with basic geometrical modification requirements, eliminated the FRP blade from the study matrix. This does not mean that composite structural materials are not suitable for the sectionalized-blade concept; on the contrary, they offer unmatched advantages over metallic structural materials. The insensitivity to stress concentration is the most important one in this case.

If a new sectionalized blade had to be designed, by dynamic, geometrical, or aerodynamic requirements, FRP would be seriously considered as the basic structural material.

BASIC DESIGN SOLUTION

The solution which evolved retains the UH-1H-type blade spar (aluminum-alloy box-shaped extrusion) and inboard aluminum-alloy-sheet laminations over the spar. But the integral aft portion of the blade (aluminum-alloy skin supported by aluminum-alloy honeycomb) is replaced over 82 percent of the blade length by FRP (fiberglass-reinforced plastic) trailing-edge boxes. A continuous trailing-edge member was retained, although its configuration changed. The requirement for the continuous trailing-edge member is dictated by the necessity for stiffness in the plane of rotation. Aluminum alloy was chosen as the trailing-edge structural material to prevent problems resulting from differences in thermal expansion between the spar and the trailing-edge member. A step-tapered trailing-edge-strip configuration was chosen in order to minimize the number of different trailing-edge box sizes. At the inboard end it features a lug (picked up by the outboard bolt of the drag strut) which allows for replacement in case of damage.

Two versions of the basic design were studied, one featuring a bolted connection between the trailing-edge boxes and the spar and trailing-edge member (Figure 18) and another featuring bonded connections (Figure 19). These two versions have some common components: the spar, blade inboard portion, and removable leading-edge portion. They differ mostly in the configuration of the trailing-edge boxes (Figures 21 and 22) and trailing-edge members (Figures 23 and 24), and, of course, in method of assembly. The rationale leading to the choice of a bolted configuration for the blade is as follows.

Spar

The blade's main structural member, the spar, is a box-shaped aluminum-alloy extrusion. Its dimensions and general shape are kept close to those of the UH-1H blade in order to use the same type and location of root-end attachment. The reasons for some deviations from the UH-1H configuration were explained in the earlier discussion.

Blade Root End

The root end is kept basically the same as the UH-1H blade to assure demonstration on a UH-1H. The location of the blade pickup bolts is identical with that of the UH-1H blade. Spar-reinforcing laminates are only slightly modified. The innermost three laminates are trimmed somewhat at their outboard

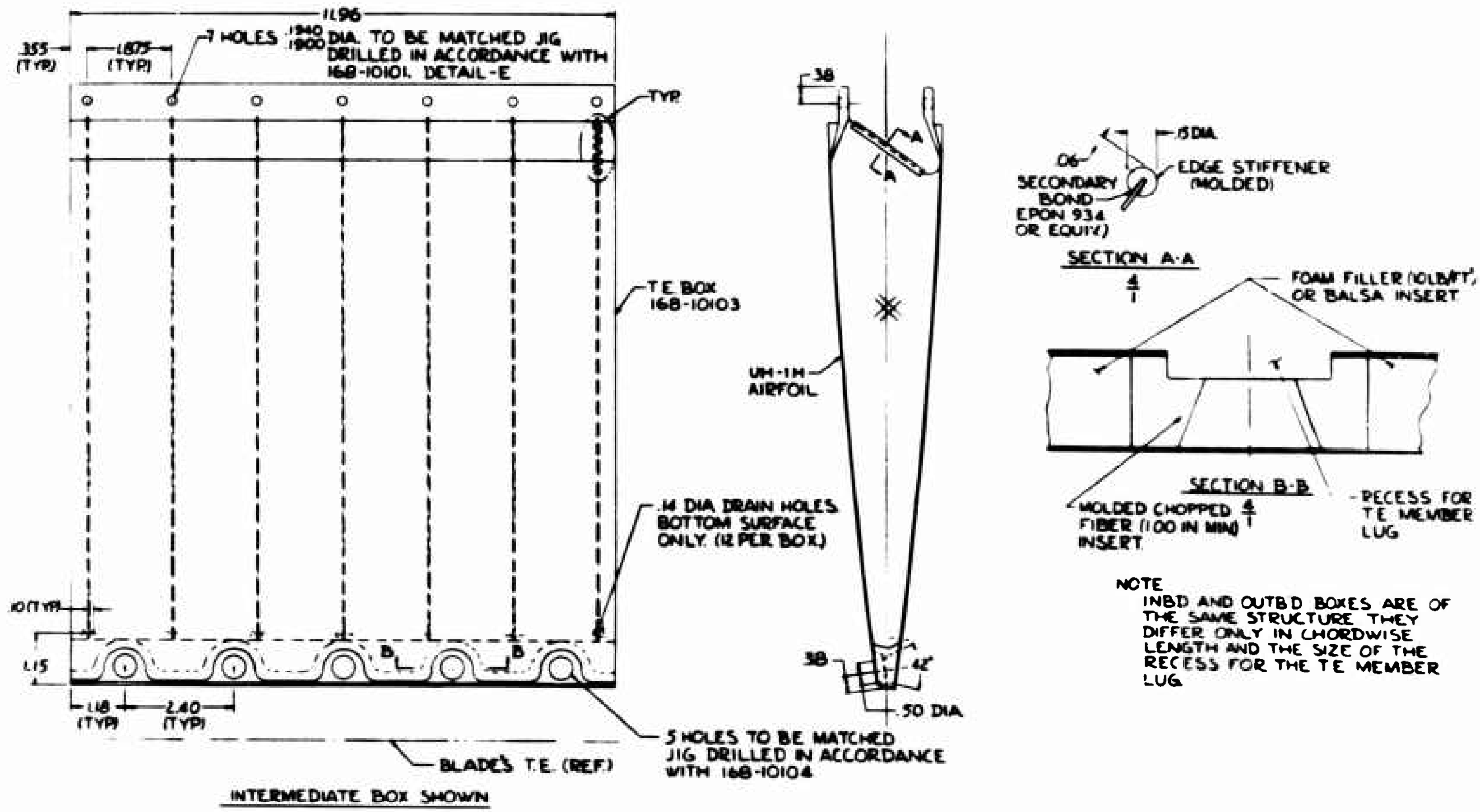


Figure 21. Trailing-Edge Box of Bolted Sectionalized Blade.

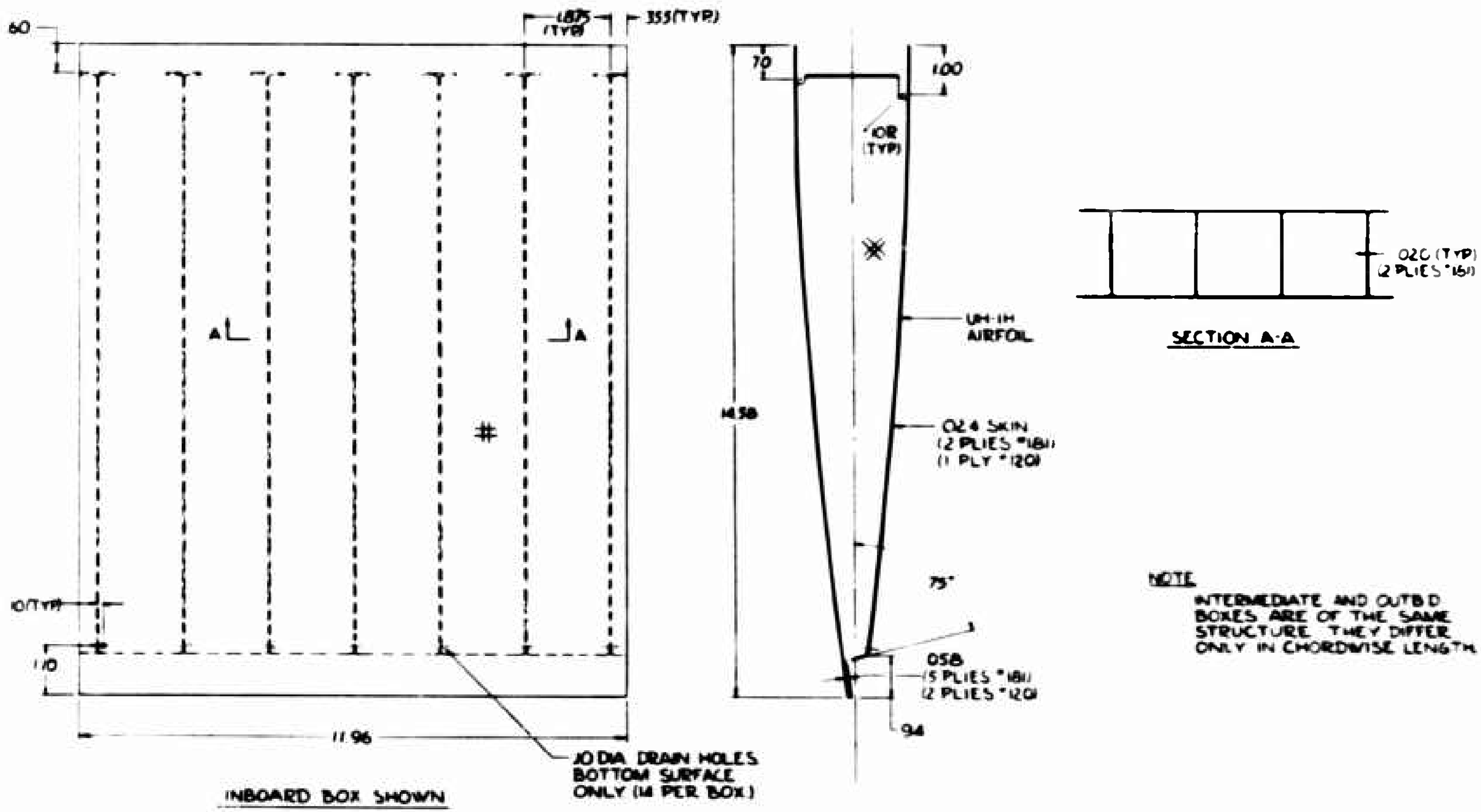


Figure 22. Trailing-Edge Box of Bonded Sectionalized Blade.

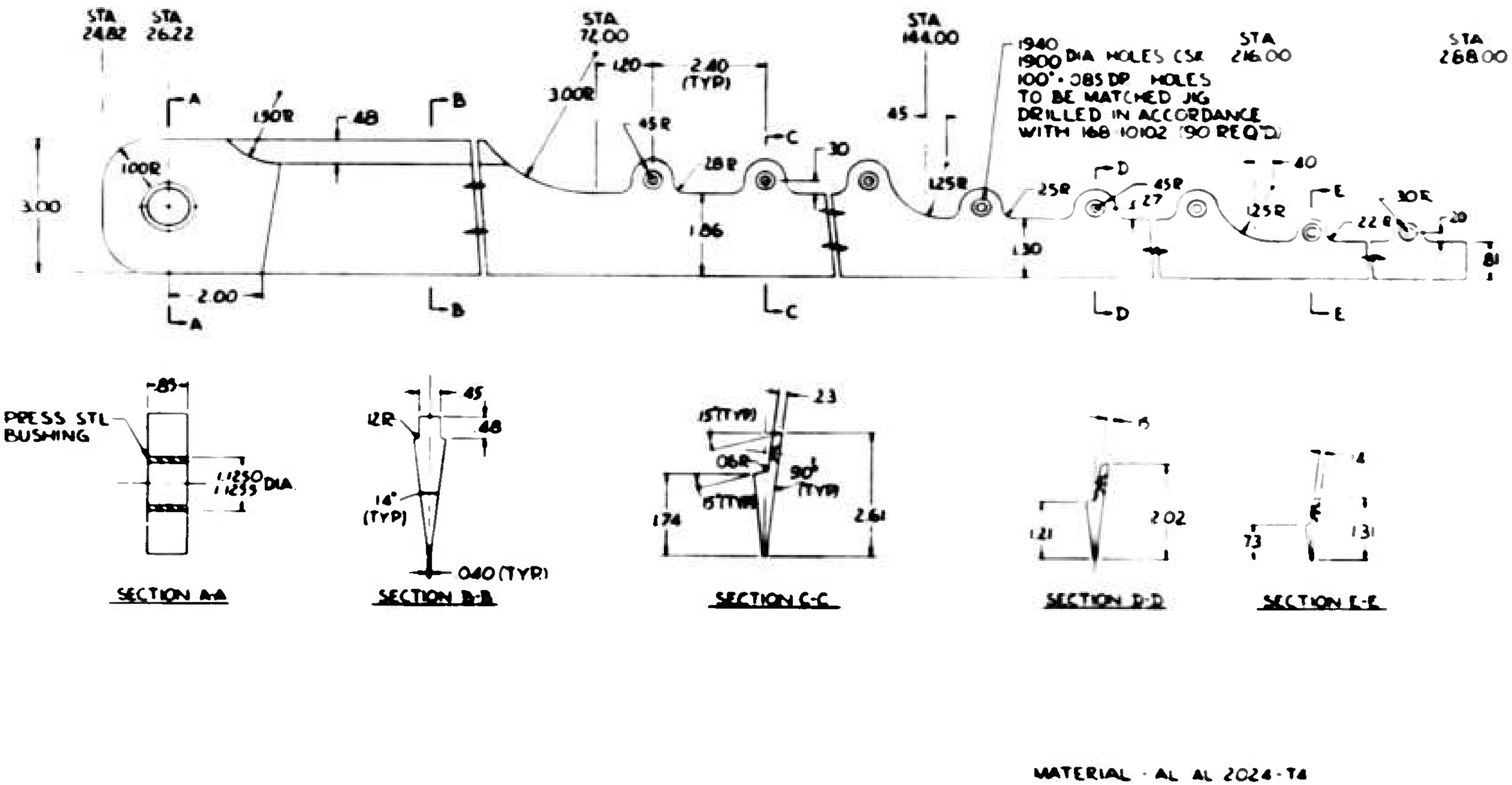


Figure 23. Trailing-Edge Member of Bolted Sectionalized Blade.

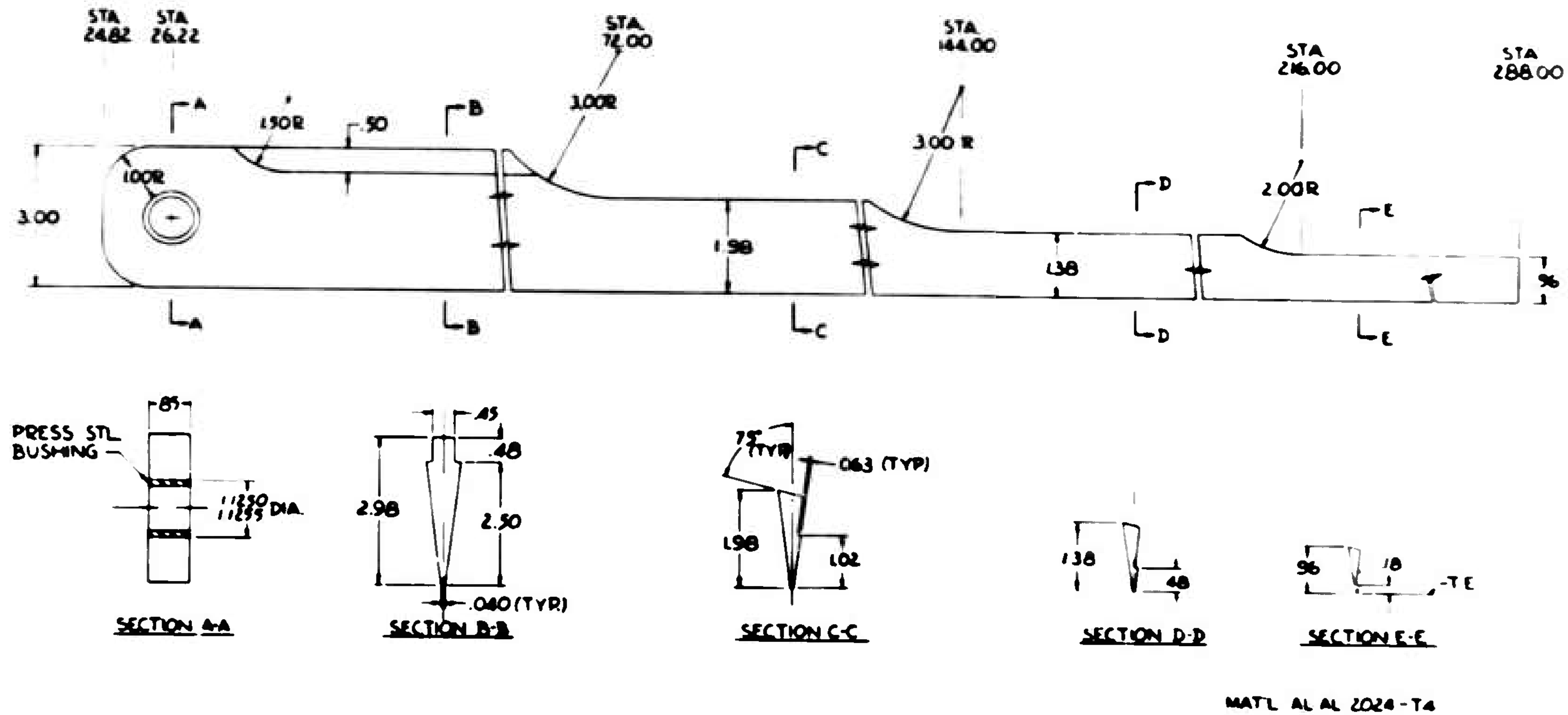


Figure 24. Trailing-Edge Member of Bonded Sectionalized Blade.

ends in order not to interfere with the first (inboard) trailing-edge box.

The trailing-edge portion of the blade root underwent major modification to accommodate the removable trailing-edge member (see Figure 25).

Some consideration was given to the idea of an integrally bonded trailing-edge member. In this case the trailing-edge portion of the blade root end would be identical to that of the UH-1H, including external laminations running along the trailing edge. This simple solution shows two disadvantages:

1. Impossibility of replacement in case of damage

2. Vulnerability prior to the installation of trailing-edge boxes (208 inches of slender member protruding out of blade structure outboard of station 72)

Consequently the separate, bolted-on trailing-edge member was selected for the sectionalized blade.

Removable Leading-Edge Member

Three different versions of leading-edge members were considered (see Figure 26 for versions 1 and 2):

1. Piano-hinge attachment

2. Wedge type

3. Bolted version

Piano-Hinge Version

A piano-hinge version provided a solution in which the leading-edge balance rod was used as a hinge connecting the male and female parts of the joint. The required manufacturing tolerances and difficulty in hinge insertion (if its length were considerable) make this solution impractical.

Wedge-Type Version

In this version, the spar retains its basic box-like shape but its front web is moved rearward and two slightly converging lips are added on the leading-edge side. These lips serve as a retainer for the leading-edge member which has its own lips spread against those of the spar by means of a tapered spreader blade. The centrifugal force on the leading-edge member must be taken by tip- or root-located attachment.

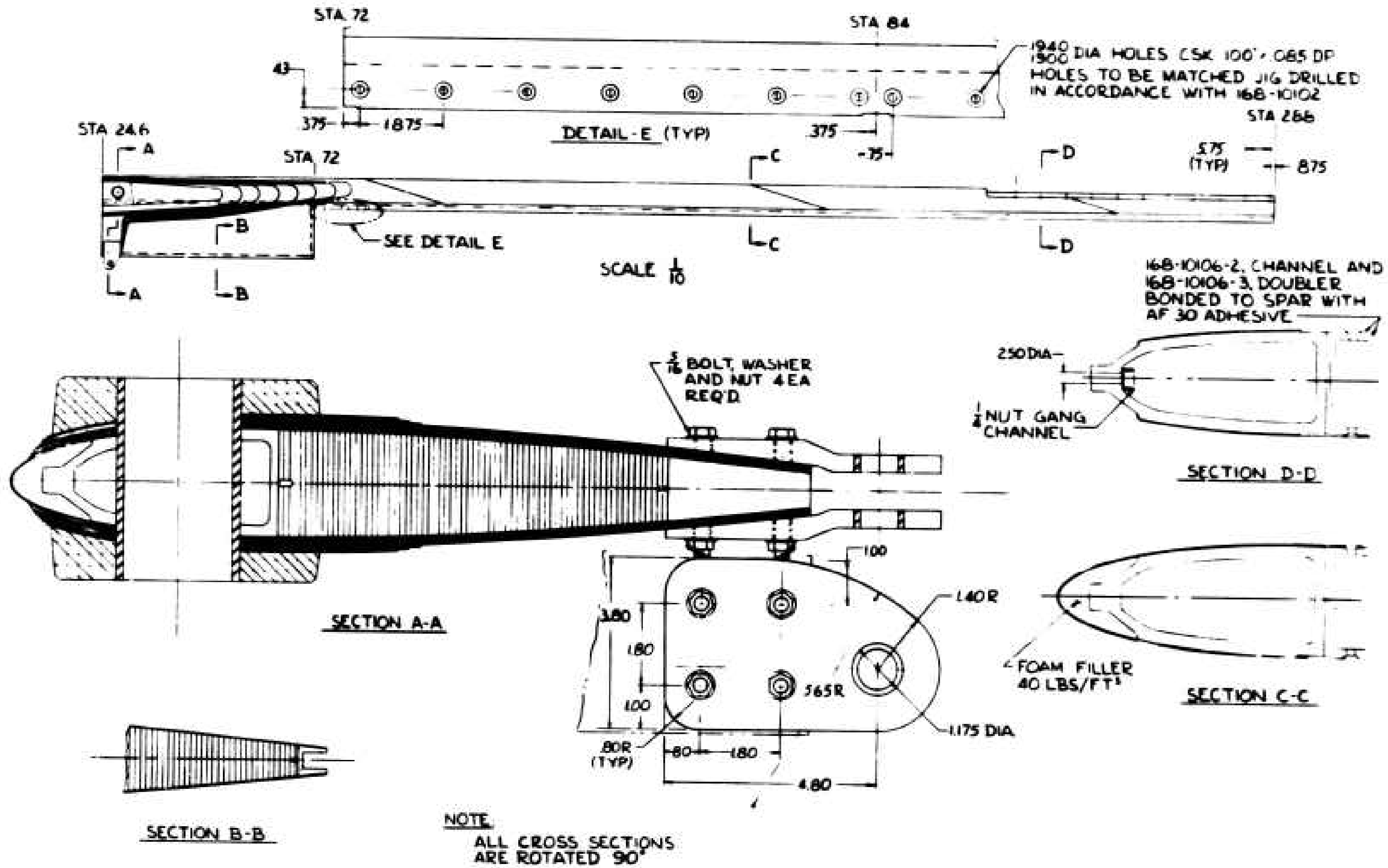


Figure 25. Main Structure of Bolted Sectionalized Blade.

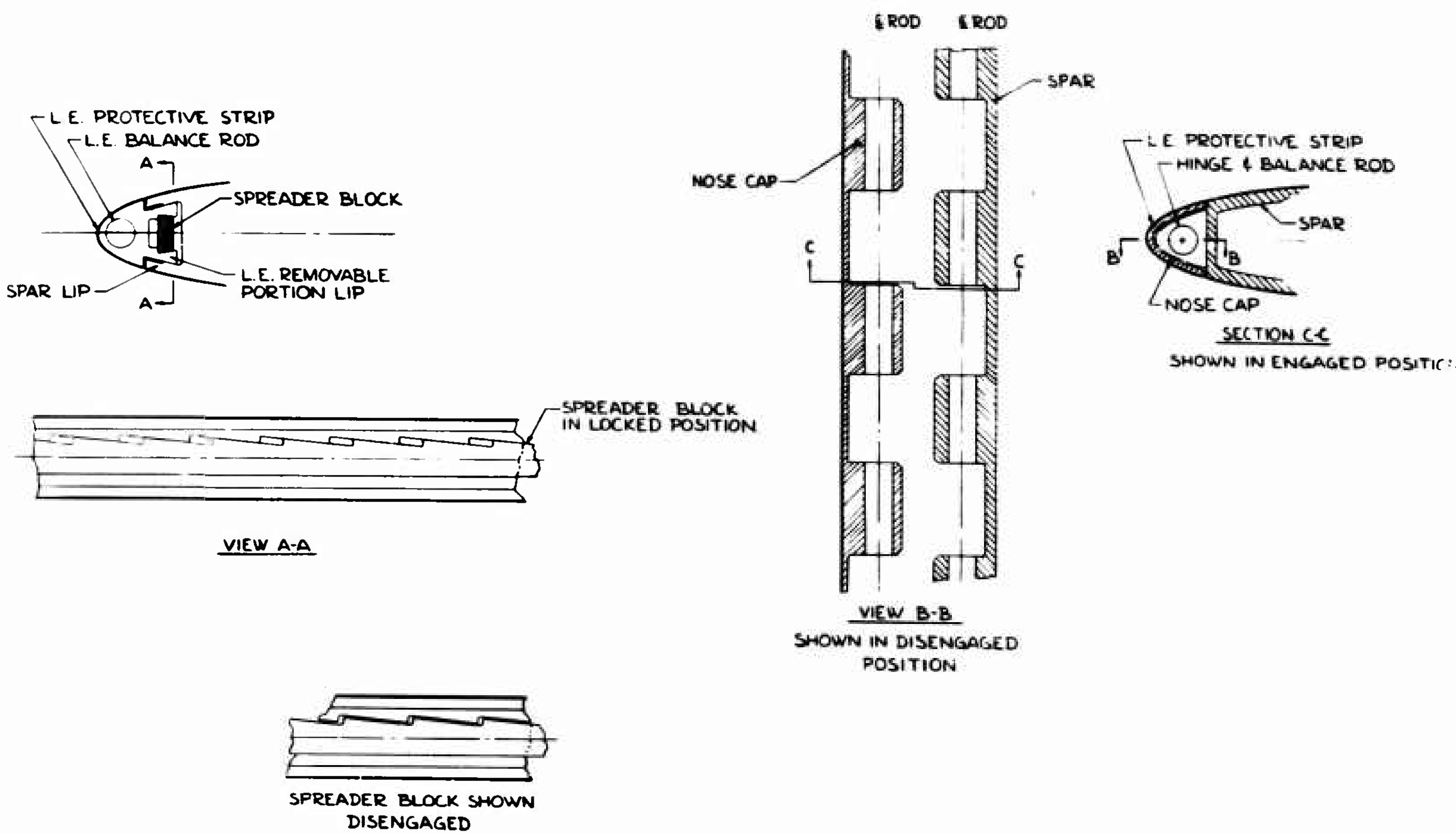


Figure 26. Removable Leading Edge Portion of the Sectionalized Blade.

Since in-depth dimension of the spreader block is limited, it would be necessary to accept a saw-type configuration of the spreader blade, with matching sloping surfaces on the inside of the leading-edge removable portion. This would require high-precision tooling.

Bolted Version (See Figure 18)

This design solution seems to be most advantageous because of its simplicity and low tooling cost. Its drawbacks are the installation of a gangnut channel inside the spar and the necessity of filing off the heads of the retaining bolts (special type).

A unique advantage of this version is a certain degree of energy absorption in case the blade strikes an object like a tree branch. In this case the leading-edge portion will not damage the blade proper under the impact, but it will spread (thus absorbing the energy) due to the fact that its contact surface with the front face of the spar is sloped.

Evaluation of these three versions led to the selection of the bolted leading-edge removable portion for the sectionalized blade.

The next decision made was the amount of blade span requiring a removable leading-edge member. It was determined that the outboard 25 percent of the blade radius should have a replaceable leading edge. This decision was based on the facts that only the outboard portion of the blade is exposed to the danger of striking a hard object (tree) and usually only the blade tip portion is subjected to damaging abrasion from sand or other hard particles.

Full-span removable leading edges are undesirable because of fretting and corrosion problems. These two problems will be present to some degree despite precautionary measures, and they will lower the allowables of materials. In this case the aluminum-alloy extrusion will be most vulnerable.

Lower stress allowables may be accepted at the blade tip where UH-1H loads are low, but not along the full span. Thus the extent of spanwise coverage was established as 25 percent of radius.

Trailing-Edge Boxes

The design and manufacturing concept of the trailing-edge box selected for the sectionalized blade is based on fiberglass-reinforced plastic (FRP) and the vacuum-pressure injection (VPI) molding technique.

In the case where, out of necessity, blade components are full of bolt holes enabling their replacement, FRP (or other fibrous material) shows clear advantages over metallic structures.

The low notch sensitivity of FRP is quite well substantiated, and the absence of corrosion problems also increases its value as a structural material. In terms of cost, a VPI-molded FRP blade box is superior to its metal counterpart, and its reproducibility (as to both shape and weight) is excellent.

It should be pointed out that an FRP box is not a must in the case of a bonded-trailing-edge blade, because there are no notches introduced by bolt holes. The other advantages of FRP cited previously still apply in recommending this material for the bonded version of the sectionalized blade.

The trailing-edge box for both blade versions (bonded and bolted) features a flexible bottom lip achieved by the relief in the rib. Its purpose is twofold: (1) to simplify the installation of the box when the trailing-edge member is in position (when trailing-edge member is removed, the box may be installed easily in forward movement in the plane of the chord), and (2) to compensate for possible variation of spar heel dimension.

A ribbed configuration of the trailing-edge box was selected rather than a honeycomb-stabilized one, for reasons of cost, simplicity, absence of water migration problems, and its adaptability to the vacuum-pressure injection (VPI) manufacturing process.

This process offers numerous advantages in the areas of economics, aerodynamics, and quality control. It belongs to the closed-dies molding method group and consists of the injection of liquid resin into the mold cavity which was first filled with dry cloth layup and from which air was previously evacuated.

This method is applicable to a variety of products, ranging from simple beams or fairings to complex structures like rotor or propeller blades. With a multicell blade as an example, the manufacturing scheme would resemble the diagram in Figure 27.

In this process, mandrels M whose shapes are defined by cell geometry are wrapped in dry cloth, first individually and later as an assembly, and placed in female split dies D whose contours are defined by airfoil geometry. Vacuum is drawn at one end of the die assembly, and liquid resin is injected at the other under pressure which varies in magnitude, depending on the resin viscosity, size of the molded product, and the resin-to-cloth ratio.

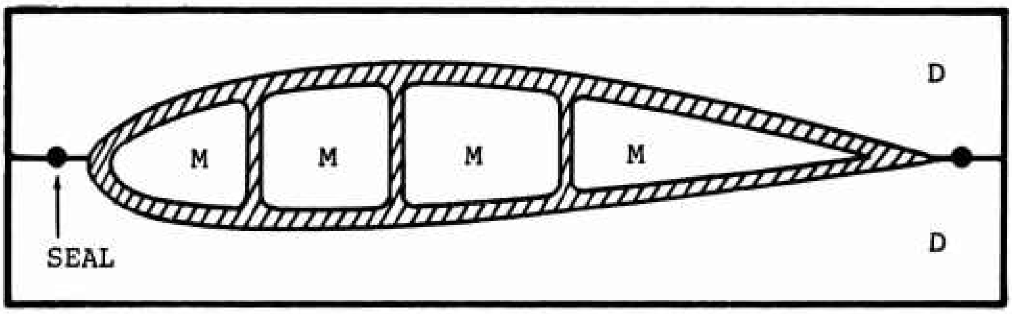


Figure 27. Vacuum-Pressure Injection Manufacturing Scheme.

The assembly is subsequently cured at a temperature and duration determined by the type of resin used. Finally, the dies are opened and the mandrels are withdrawn, yielding the end product in one molding operation. The process looks very simple, but there are many trade secrets and skills which must be employed to overcome development problems. Once they are mastered, the advantages of the VPI method make this process extremely attractive. The VPI method has many advantages which can be categorized as follows:

<u>Manufacturing</u>

1. Simple tooling concept
2. Excellent reproducibility
3. Minimum of manufacturing operations
4. Absence of pressure bags and vacuum bags
5. Minimum need of special facilities such as autoclaves, presses, etc. Only an oven is required.

<u>Structures</u>

1. No secondary bonded joints in primary structure
2. No delaminations, inclusions, or similar defects

<u>Aerodynamics</u> (if blades or wings are produced)

1. Outstanding airfoil contour tolerances
2. Excellent surface smoothness

<u>Quality Control</u>

1. One curing operation
2. No bonded joints in primary structure

<u>Weights</u>

1. Very good weight control from piece to piece (when molded in the same set of tools)

<u>Economics</u>

1. Potentially lowest production cost (one-shot product)
2. Inexpensive tooling

However, there are disadvantages which must be taken into consideration:

1. Weight penalty resulting from the use of woven fabric, rather than unidirectional fibers (i.e., roving or tape) which have higher static and fatigue properties.

2. The use of cloth in dry layup is dictated by the necessity for holding the fibers in the required pattern. Loose layup could easily be distorted by the flow of liquid resin.

3. Design and tooling problems created by the necessity of mandrel withdrawal.

4. Automatic layup is not practical for complex parts.

The trailing-edge box is 12 inches long and features 7 ribs. These characteristics were selected on the following basis:

1. Existing manufacturing experience with CH-46 trailing-edge boxes

2. Geometry of the UH-1H blade

3. Repair and maintenance criteria

The CH-46 trailing-edge box (FRP molding) was designed and stressed for conditions similar to those of the UH-1H, as far as size and airloads are concerned. The outcome was very satisfactory, and, in order to reduce the risk of the development, it was decided to use the existing experience.

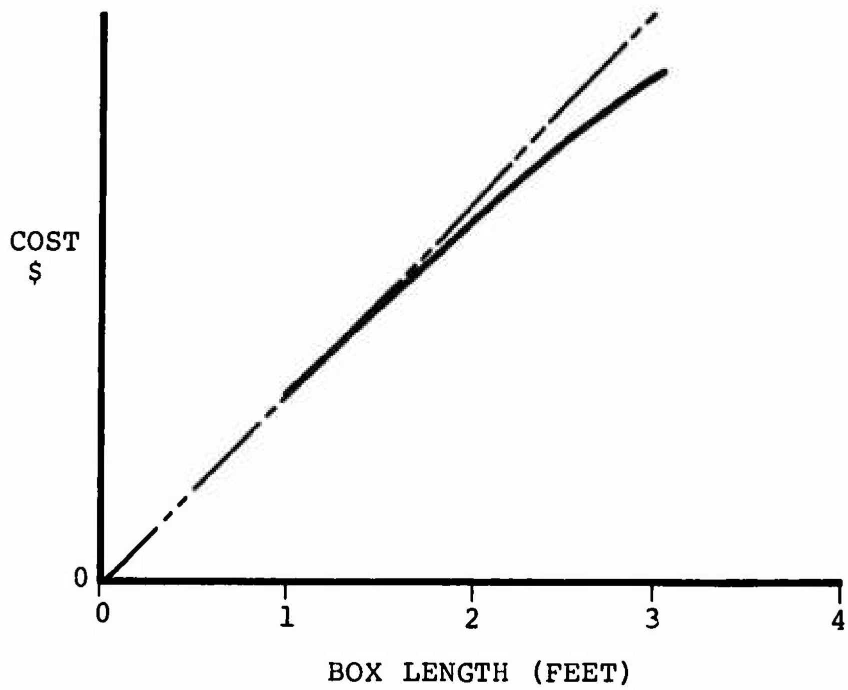
The UH-1H blade features a rather high degree of twist: nearly 1/2 degree per running foot. No difficulties are expected in the installation of the trailing-edge box without built-in twist on the UH-1H twisted spar as long as the box is only 1 foot long. The same operation with a 3-foot-long box would be difficult, if not impossible, in the presence of the trailing-edge member and would cause aerodynamic problems, elastic stress preload in the box, or both.

The number of machine screws attaching the trailing-edge box to the basic blade structure is dictated by the number of ribs per box (i.e., 7 ribs). It was considered advisable to locate attaching elements close to the shear-carrying ribs. A smaller quantity of machine screws of the given size (No. 10) would not be sufficient from the point of view of stress (see the appendix on stress for details).

This configuration (7 ribs and 7 machine screws) could be changed if test data were available to justify a reduction in the number of these elements.

From the repair and maintenance point of view, the short box requires minimum replacement time (assuming one-hit damage to the blade). In terms of cost, the short box offers an advantage in the case of a one-hit assumption since the cost of the trailing-edge box is, in the first approximation, proportional to its length.

Qualitatively, a cost-versus-box-length curve would have the shape shown below:



After all the factors discussed here were taken into consideration, a 12-inch-long trailing-edge box was selected for the sectionalized blade.

Trailing-Edge Member

The bolted trailing-edge member (Figure 23) is a separate part attached to the root end of the blade by the same bolt which picks up the drag brace of the UH-1H blade; the length of the bolt itself has to be increased. The trailing-edge member features an integral lug at its inboard end and a series of holes for trailing-edge box attachement; there are no holes in the bonded version.

There are forging presses available with beds large enough to forge the full-length trailing edge; hence, machining operations on the trailing-edge member can be reduced to a minimum.

The presence of holes in the trailing-edge member creates design and stress problems. In order to reduce the detrimental effect of the holes on the strength of the trailing-edge member, it was decided to drill the holes through protruding lugs and not through the body of the trailing-edge member. With careful design of the lug configuration, the flow of compressive or tensile stresses will not be highly concentrated. This solution created a new problem: that of housing the lugs in matching recesses in the trailing-edge boxes.

Forward lips on the trailing-edge boxes fit between corresponding lips on the blade spar assembly. Both are predrilled in precisely coordinated jigs; consequently, there will be no necessity of in-the-field drilling or reaming which in turn would involve reinstallation of basket nuts mounted on the inside surface of the trailing-edge box lip.

The trailing-edge member is not bolted to the blade between stations 28 and 72; stiffness in the plane of rotation is large enough to prevent instability. Buckling in the plane of flapping is prevented by nesting the trailing-edge member in the channel which closes the trailing-edge side of the blade proper. Fretting is prevented by the application of Teflon tape to the trailing-edge member. Outboard of station 72 the trailing-edge member is step-tapered (3 steps). The incorporation of linear thickness taper on the UH-1H would involve the necessity of using 18 different trailing-edge boxes, which is prohibitive from a maintenance and repair point of view and would involve serious spare parts problems. A constant-cross-section trailing-edge member would result in only one size of trailing-edge box, but it would create an unacceptable weight penalty. A 3-stepped trailing-edge member with 3 sizes of trailing-edge boxes is an acceptable compromise between these two contradictory requirements.

SUMMARY EVALUATION OF SELECTED DESIGNS

In the final evaluation of the design arrangements of the sectionalized blade, two solutions, shown on Figures 18 and 19, will be taken into consideration.

Both solutions feature an aluminum-alloy extrusion as a basic structural member with UH-1H-type laminations reinforcing the blade at its root end, a replaceable outboard portion of the leading edge, a replaceable trailing-edge member, and 18 FRP trailing-edge boxes in 3 sizes.

The two configurations differ radically in the method of assembly of trailing-edge boxes to the spar and trailing-edge member. One is based on a bolted assembly; the other, on a bonded assembly. Many factors must be taken into consideration in evaluation of these two design arrangements. The factors are listed in Table IX and the values A, B, or C are allotted to each factor (A being the highest). Some explanatory remarks concerning Table IX are in order.

TABLE IX. COMPARATIVE EVALUATION OF SELECTED DESIGNS		
Factor	Bolted Assembly (Figure 18)	Bonded Assembly (Figure 19)
<u>Cost</u>		
Tooling	C	A
Blade Proper	C	A
<u>Design</u>		
Weight	C	A
Aerodynamic Properties	B	A
Dynamic Properties	C	A
Unknown Factors (Risk)	C	A
<u>Maintenance and Repair</u>		
Replacement Time of Components	A	C
Possibility of Replacement Without Blade Removal	A	B
Effect of Environmental Conditions	A	C
Tools and Equipment Needed for Replacement	A	C

Cost

Tooling

Although all major metal components (except for the trailing-edge member) are identical in both versions, the cost of tooling will be substantially higher for the bolted configuration of trailing-edge boxes. This is due to the complexity of tooling for the bolted-type trailing-edge boxes and mainly due to the necessity for very precise, matched drilling and reaming jigs which will be required for proper coordination of bolt holes in the blade spar and the trailing-edge member. Without high-precision tooling, the idea of field-replaceable trailing-edge boxes would be impractical.

Blade Proper

Two elements of the bolted blade--the trailing-edge box and the trailing-edge member--will require considerably more man-hours to manufacture (the trailing-edge member especially, due to its scalloped configuration).

Design

Weight

In this case there is a clear-cut superiority of the bonded version.

Aerodynamic Properties

The presence of 252 heads of No. 10 machine screws (not counting trailing-edge member screws which will degrade aerodynamic properties to a lesser degree) will significantly affect blade drag. The surface smoothness of the bonded blade will be superior, although inferior to that of the current UH-1H blade.

Dynamic Properties

It is easier to match the UH-1H dynamic properties with the lighter bonded blade than with the heavier bolted one.

Risk - Unknown Factors

Although the mechanical properties of FRP are in general well substantiated, very little is known about the fatigue properties of bolted joints. Limited information is available from McDonnell-Douglas Corporation tests published in the report "Investigation of Joints in Advanced Fibrous Components for Aircraft Structures". It is not sufficient, however, to establish the shape of the S/N curve. Consequently, stress analysis of the trailing-edge box bolted joints was based on certain assumptions which, under normal conditions, should be confirmed by series of tests prior to presenting the drawings incorporating such a joint. This is the only major unknown factor in the sectionalized blade study.

Repair and Maintenance

Time of Replacement of Trailing-Edge Box

With the leading-edge removable portion being identical, only the trailing-edge box replacement will be discussed here.

In this case, the bolted assembly offers undeniable superiority. A single trailing-edge box may be replaced within approximately 40 minutes by unscrewing 19 No. 10 machine screws, snapping the new box into position, and replacing the 19 machine screws.

It will take 4 to 6 hours (depending on length of curing time) to remove the damaged trailing-edge box in the case of the bonded version of the blade, clean the contact surfaces, apply the bonding medium, snap the new box into position, and apply pressure and heat (if an accelerated cycle is used). It is conceivable that different adhesive bond requirements could be applied to reduce the replacement times of trailing-edge boxes, depending on the spanwise location.

For instance, the very inboard box, lightly loaded and located in a low-g field, may be made safe for flight in a fraction of the time required for curing the bond of an outboard box near the tip.

The use of electrically cured bonding tape may substantially shorten box installation time.

Possibility of Component Replacement Without Blade Removal

In the case of the bolted assembly, any or all boxes and the leading-edge member may be easily replaced in the field without removing the blade from the rotor hub. Besides the screwdriver, a ladder and some kind of blade tip support would be necessary. The latter would be required to reduce the effect of blade droop on the change in spacing between bolt holes (especially in the row of holes for box-to-spar attachment).

Trailing-edge member replacement without blade removal would be undesirable due to its length and the flimsiness of the vulnerable tip portion.

Repair without blade removal may also be possible on the bonded blade except that the screwdriver would be replaced by tools or equipment necessary for the bonding operation and the use of this equipment would be more difficult when operating from a ladder.

Effect of Environmental Conditions

In the case of the bolted assembly with matching, jig-drilled and reamed holes in blade components, there is only one tool required for box replacement: a screwdriver. As a consequence, there will be no effect of extreme cold conditions on the replacement of blade components except for the somewhat longer time required due to the awkwardness of working in heavy gloves and other clothing. A sandstorm or monsoon rain may also increase the time of this operation. Generally, however, the effect of these conditions will be small as compared with the case of the bonded assembly. Cold, rain, or sandstorm will necessitate the installation of some kind of protective hood covering the area where replacement is necessary. Again, extreme cold conditions would be most difficult to work in and would require some kind of heater which could raise the temperature under the hood to the level required by the chosen adhesive. Here again, the use of an electrically heated adhesive film would have a beneficial effect on the hardship and time of component replacement.

Tools and Equipment Needed for Replacement

For replacement of components on the bolted blade assembly, the following tools are required:

1. Trailing-edge boxes - screwdriver

2. Leading-edge member - screwdriver, hacksaw, and file

3. Trailing-edge member - screwdriver and mallet

The hacksaw is needed to cut slots in the filed-off heads of the attachment bolts. The file is used to file off the heads of the replacement bolts. For the replacement of blade components without blade removal, the previously mentioned ladder and blade support would be required.

For replacement of trailing-edge boxes on the bonded blade assembly at room temperature, the following tools and equipment are required: hacksaw, chisel, pliers, and a special tool for exerting pressure on bonded areas, plus all equipment needed for the cleaning and bonding operation (sandpaper, acetone, spatula, and cans of bonding medium plus mixing container).

Repair work on the bonded blade at extremely low temperatures would require all the equipment mentioned in the previous paragraph, plus a hood and a heater.

In spite of some advantages of the bonded blade assembly listed in the comparison table, the most important factors (maintenance and repair) make the bolted assembly more attractive than its bonded counterpart. It is this contractor's opinion that this blade will serve the purpose outlined in the contract requirements better than the alternative bonded assembly.

Thus, the blade shown on Figure 18 becomes the preferable design arrangement in the Sectionalized Main Rotor Blade Advanced Design Study.

From the design point of view, the most objectionable feature of the bolted assembly is the risk factor resulting from many unknowns concerning the simple lap-bolted joint: shape of S/N curves, effect of nut torque, effect of fit between bolt and hole, etc. These unknowns can be easily eliminated by instituting a confirmation test program.

SECTION III

SELECTED DESIGN ARRANGEMENT

CONFIGURATION DESCRIPTION

The preferred design arrangement of the sectionalized blade is shown in Figure 18.

The main components of the preferred design are: the spar (integral with wide inboard portion and its external laminations), 18 trailing-edge boxes in 3 different sizes, trailing-edge member, and leading-edge portion.

Basic Blade Structure (See Figure 25.)

The spar, the blade's main structural member, is cut to size from an aluminum-alloy extrusion, machined where required, and twisted. The shape and size of this extrusion differ from the current UH-1H blade. Its width was increased from chordwise station 5.4 inches to 6.0 inches to compensate for the loss of torsional stiffness resulting from replacement of the torsionally rigid UH-1H blade aft portion of the airfoil cross section by short (12-inch) trailing-edge boxes. The front portion of the spar extrusion was shaped keeping in mind the installation of the removable portion of the leading edge.

The inboard forward portion of the blade is similar to the UH-1H blade as far as the shape of external laminations is concerned. The inboard rear portion is modified; external laminations do not extend along the trailing edge but end under the pad through which the drag-strut bolt passes. The rear closing member is in the form of a channel, open to the rear, which houses the trailing-edge member between stations 28 and 72. As in the UH-1H blade, honeycomb is used to stabilize the blade's aft portion skin inboard of station 72. This basic blade metal structure is shown on Figure 25.

It was concluded during the early stage of this design study that it would be inadvisable to drill the holes for bolted attachment of the trailing-edge boxes through the basic metal structure of the spar. To transfer the loads from trailing-edge boxes to the spar, FRP structure is bonded to the rear portion of the spar. It consists of three separately molded units: a channel and two doublers. When bonded to the spar, these elements transfer box airloads by shear only. Both doublers and the channel are molded using 45-degree-oriented S-glass No. 181 fabric. This orientation was selected to match the coefficient of thermal expansion with that of the spar and to increase shear tear-out characteristics of the bolted joint. The assembly described here constitutes the basic blade structure, which cannot be easily repaired under field conditions.

Trailing-Edge Box (See Figure 21.)

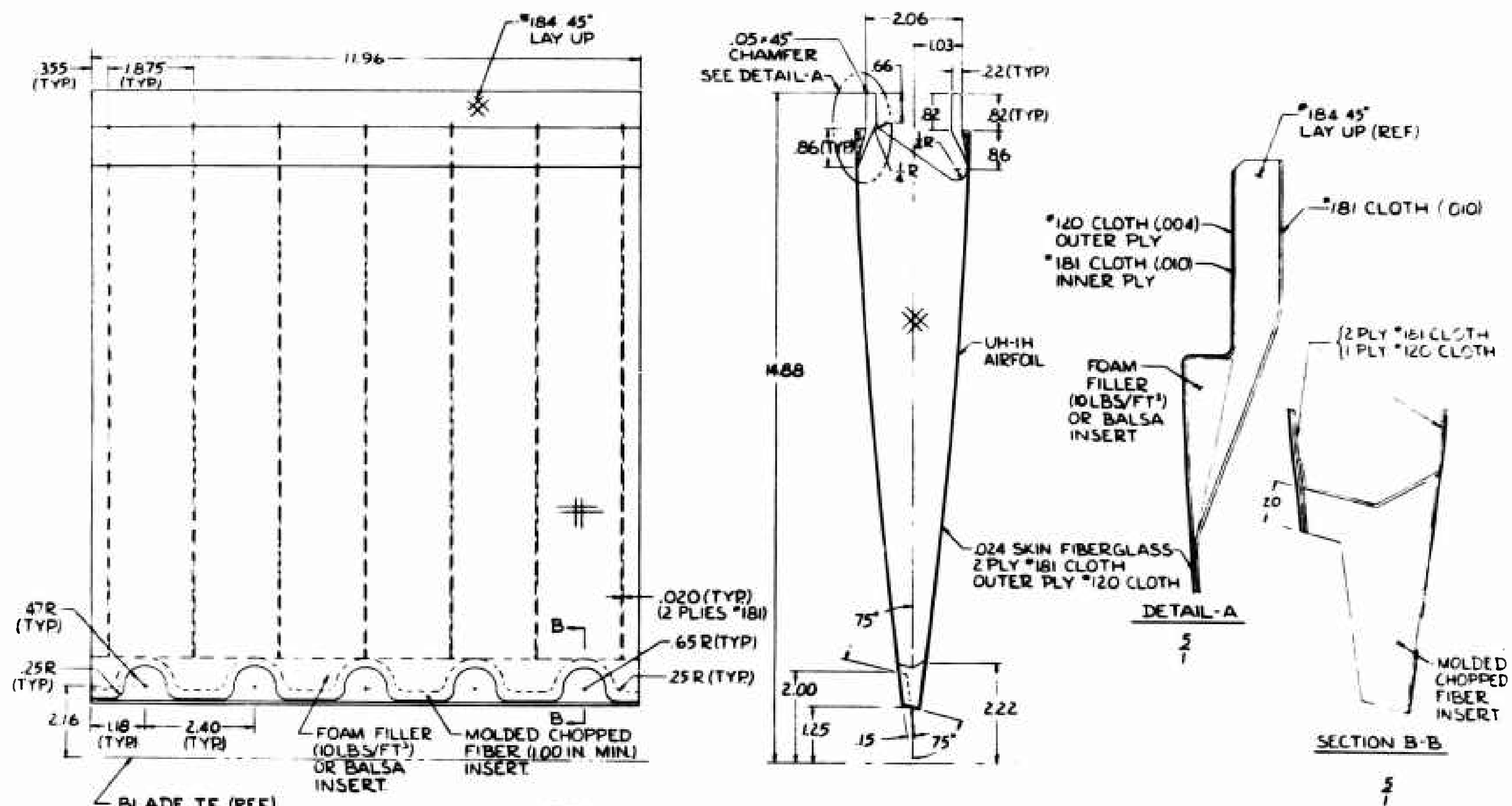
Trailing-edge boxes are attached to the spar and to the trailing-edge member by a series of small bolts (No. 10 machine screws). This feature constitutes the main advantage of the selected blade configuration, since it allows for easy replacement of the damaged box under all environmental conditions. Three different sizes of trailing-edge boxes are manufactured in a one-shot operation using E-glass No. 181 cloth molded with epoxy resin. The boxes feature 7 ribs integral with the box structure. Two lips, 0.22 inch thick, on the front edge of the box transfer the loads to the spar by means of a single lap-bolted joint. The upper joint transfers vertical shear and bending moment (by means of a couple); the lower one, bending moment only. In this manner a statically determinate structure is obtained. Flexibility of the box skin between the lip and ribs provides a design solution which also offers another advantage: the possibility of establishing firm contact between the lips of the box and the channel without inducing stresses in these elements. There is no danger of loss of stability of the lower skin since, under flight conditions, it is always loaded in tension. Local flexibility of the lower skin offers still another advantage, that of easy installation. When the trailing-edge member is in position, it is impossible to install the box by simple forward movement in the plane of the chord. A combination of rotation and in-plane movement is necessary and, in this case, flexibility of one skin makes box installation easy. A molded chopped-fiber insert with recesses to house the lugs of the trailing-edge member is located at the aft edge of the box.

After being molded (see Figure 28), the box undergoes a hole-drilling operation at the front and rear edges and the installation of basket nuts on the inside surface of both front lips.

It should be noted that the drilling and reaming operations require precision in order to assure simultaneous matching of holes in the spar, boxes, and trailing-edge member. The use of matched drilling fixtures is mandatory.

Trailing-Edge Member (See Figure 23.)

The trailing-edge member is a single unit of variable cross section machined from aluminum-alloy bar (or a forging in



NOTES
1. T.E. BOX MOLDED AS A UNIT BY VACUUM-PRESSURE-INJECTION (VPI) OR EQUIVALENT METHOD.
2. INB'D AND OUTB'D BOXES ARE OF THE SAME STRUCTURE. THEY DIFFER ONLY IN CHORDWISE LENGTH & THE SIZE OF THE RECESS FOR T.E. MEMBER LUG.

Figure 28. Molded Trailing-Edge Box of Bolted Sectionalized Blade.

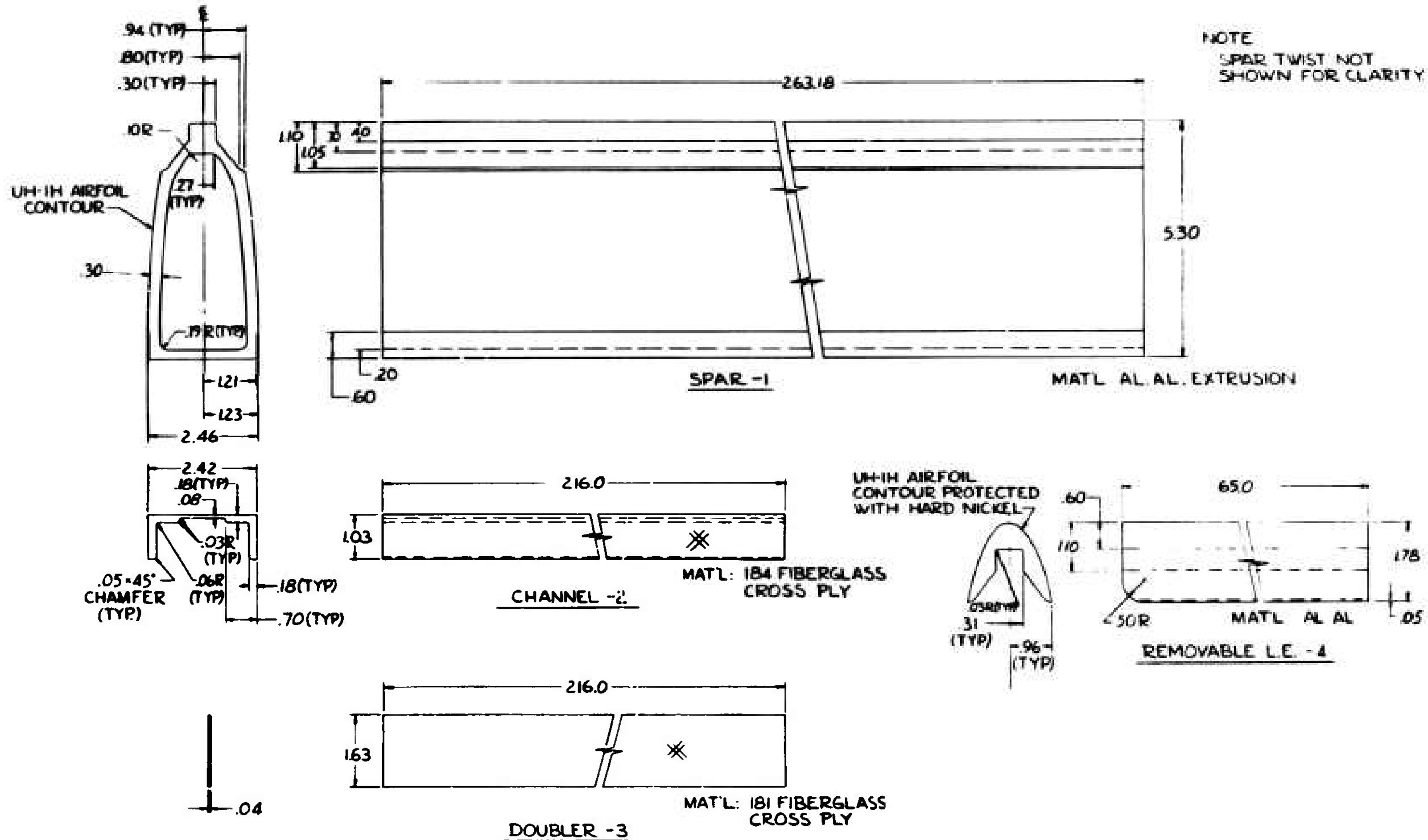


Figure 29. Details of Bolted Sectionalized Blade.

production) with an integral lug at the inboard end which serves as an attachment to the blade root-end structure by means of the drag-strut bolt. Aluminum alloy was selected as the structural material in order to prevent blade bowing in extreme temperatures (the blade spar is also aluminum alloy). The cross section of the trailing edge is reduced in four steps. Three outer zones are provided with lugs for trailing-edge box attachment.

It should be pointed out that the Figure 18 blade with trailing-edge member per Figure 23 does not match precisely the in-plane stiffness of the UH-1H blade. The first-mode in-plane frequency at operational rpm is 1.1235 versus 1.2153 on the UH-1H blade. If this discrepancy is considered too large, the in-plane stiffness of this blade can be increased by converting a certain percentage of the cross section of the trailing-edge member from aluminum alloy to boron fibers. The high modulus of elasticity of boron fibers (34×10^6 lb/in.^{2}) would bring blade stiffness to the UH-1H level without upsetting blade balance. Boron fibers bonded to the surface of the trailing-edge member would be protected by a glass cloth sheet.

Leading-Edge Portion (See Figure 29, Removable L.E.-4.)

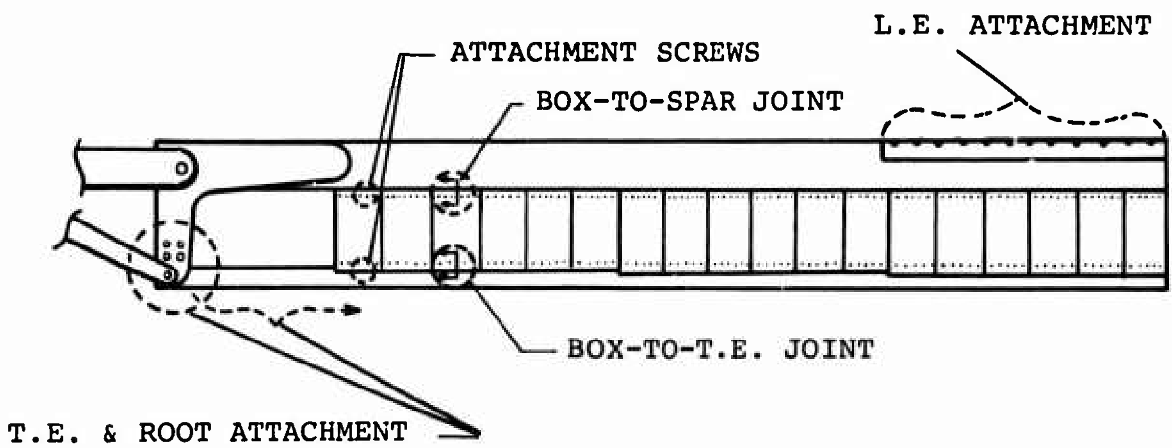
The removable leading-edge portion, which also serves as blade overbalance, is attached to the spar by means of ten 1/4-inch bolts. It is machined out of aluminum-alloy bar and carries protection against sand abrasion.

STRESS ANALYSIS AND DYNAMIC COMPARISON OF SELECTED DESIGN ARRANGEMENTS

The following paragraphs summarize the comparison of loads, frequencies, and blade properties of the UH-1H blade and the sectionalized blade and the fatigue and ultimate margins for those portions of sectionalized blade requiring detailed analysis. There were some variations between the blades in the weights, loads and frequencies. However, the similarity of the characteristics of the blades indicates that a direct replacement could be made without changing the performance characteristics of the UH-1H helicopter. Positive margins exist for both fatigue and ultimate load conditions for portions of the blade analyzed.

The loads were obtained for the following conditions:

a. 120 knots forward flight
b. Level flight
c. Sea level
d. 324 rpm



SECTIONS ANALYSED

Detailed Stress Analysis

1. Attachment Screws (AN 509 #10)

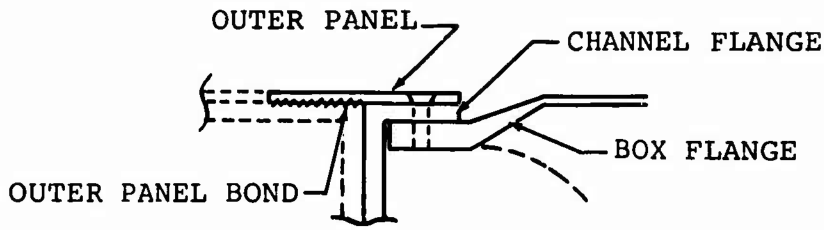
a. Box-To-Spar Attachment Screws

(1) Ultimate shear M.S. = +3.94
(2) Fatigue shear M.S. = + .14

b. Box-To-T.E. Attachment Screws

(1) Ultimate shear M.S. = +30.
(2) Fatigue shear M.S. = +27.

2. <u>Box-To-Spar Joint</u>



a. Box Flange

(1) Ultimate tensile M.S. = +1.5
(2) Fatigue tensile M.S. = + .011
(3) Ultimate shear M.S. = +5.05
(4) Fatigue shear M.S. = +1.66

b. Outer Panel

(1) Ultimate tensile M.S. = +4.05
(2) Fatigue tensile M.S. = +1.38

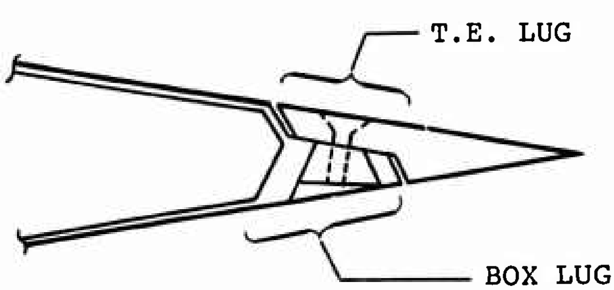
c. Outer Panel Bond

(1) Ultimate shear M.S. = +4.9
(2) Fatigue shear M.S. = +1.68

d. Channel Flange and Panel

(1) Ultimate tensile M.S. = +2.57
(2) Fatigue tensile M.S. = + .52
(3) Ultimate shear M.S. = +4.93
(4) Fatigue shear M.S. = +1.54

3. <u>Box-To-T.E. Joint</u>



a. T.E. Attachment Lug

(1) Ultimate tensile

(a) Sta. 72 → Sta. 144 M.S. = +13.10
(b) Sta. 144 → Sta. 216 M.S. = +10.70
(c) Sta. 216 → Sta. 288 M.S. = +15.0

(2) Fatigue tensile

(a) Sta. 72 → Sta. 144 M.S. = + 3.1
(b) Sta. 144 → Sta. 216 M.S. = + 3.52
(c) Sta. 216 → Sta. 288 M.S. = + 6.31

b. Box Attachment Lug

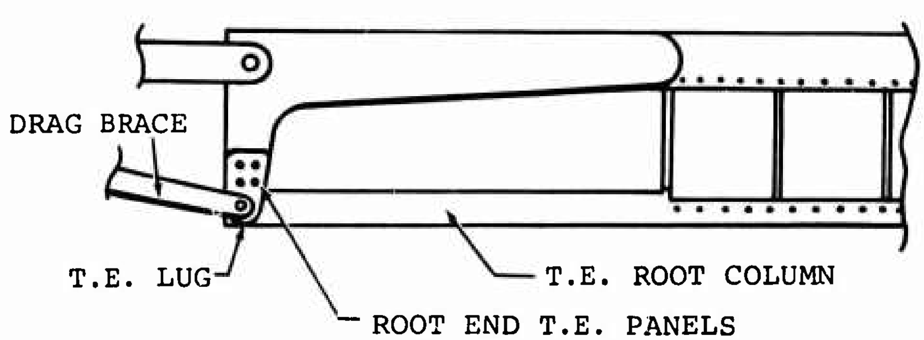
(1) Ultimate shear

(a) Sta. 72 → Sta. 144 M.S. = + 1.25
(b) Sta. 144 → Sta. 216 M.S. = + .80
(c) Sta. 216 → Sta. 288 M.S. = .96

(2) Fatigue shear

(a) Sta. 72 → Sta. 144 M.S. = + .58
(b) Sta. 144 → Sta. 216 M.S. = + 1.29
(c) Sta. 216 → Sta. 288 M.S. = + .22

4. <u>Trailing Edge and Root Attachment</u>



a. Root End T.E. Panels

(1) Main Hole

(a) Ultimate tensile M.S. = +3.95
(b) Fatigue tensile M.S. = + .35

(2) Bolts

(a) Ultimate shear M.S. = +1.69
(b) Fatigue shear M.S. = + .09

(3) Plate stress across first two holes

(a) Ultimate tensile M.S. = +3.79
(b) Fatigue tensile M.S. = + .60

b. T.E. Lug Attachment

(1) Ultimate tensile M.S. = +1.9
(2) Fatigue tensile M.S. = + .18

c. T.E. Root Column Buckling

(1) Ultimate Buckling M.S. = +2.21

d. T.E. Stress (Max)

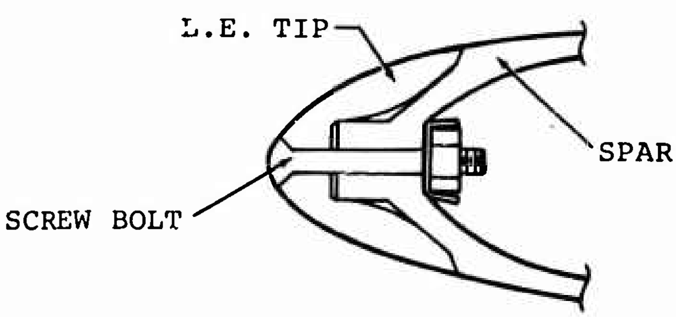
(1) Ultimate tensile

(a) Sta. 28 → Sta. 72 M.S. = +1.06
(b) Sta. 72 → Sta. 144 M.S. = + .03
(c) Sta. 144 → Sta. 216 M.S. = + .22
(d) Sta. 216 → Sta. 288 M.S. = +3.3

(2) Fatigue tensile

(a) Sta. 28 → Sta. 72 M.S. = +1.64
(b) Sta. 72 → Sta. 144 M.S. = + .001
(c) Sta. 144 → Sta. 216 M.S. = + .02
(d) Sta. 216 → Sta. 288 M.S. = + .47

5. <u>L.E. Tip Attachment</u>



a. Attachment Bolts

(1) Ultimate shear M.S. = + .70
(2) Fatigue shear M.S. = + 4.37

b. L.E. Tip

(1) Ultimate tensile M.S. = +31.8
(2) Fatigue tensile M.S. = + 6.2

c. Spar L.E.

(1) Ultimate tensile M.S. = + 3.75
(2) Fatigue tensile M.S. = + 6.69

Comparative Analysis

The comparative analysis is summarized in the following five subsections: stiffness distribution, mass distribution, frequency, loads, and dynamic balance axis.

1. Stiffness Distributions

Figure 30 presents the flapwise stiffness (EI_F) for the UH-1H production blade and the bolted design of the sectionalized UH-1H blade. The two blades are relatively close in this parameter. Figures 31 and 32 present the chordwise stiffness (EI_C) and chordwise neutral axis (N.A.) for both blades. The chordwise stiffness for the bolted design is substantially lower than that for the production UH-1H. This is primarily due to changing the box from a continuous aluminum skin with honeycomb core to segmented fiberglass boxes, and a change in T.E. The change made to the spar to make the two blades compatible in torsional stiffness was not sufficient to equalize the chord stiffness. This reduced chord stiffness is reflected in the loads used for the stress analysis and therefore had no adverse effects on the blade structural integrity of the components analyzed. However, it remains to confirm that there is no adverse effect on the UH-1H performance. Figure 33 presents the torsional stiffness (GJ) for the two blades. The spar was increased in chordwise dimension for the bolted design blade so as to make it compatible torsionally with the production UH-1H blade.

2. Mass Distribution

Figures 34 and 35 present the weight distribution and CG for the two designs. Both the weight and the CG are compatible between the two blades, with the bolted design being 5.2 pounds heavier. Figure 36 presents the polar weight moment of inertia about the pitch axis for the two designs. The polar weight moment of

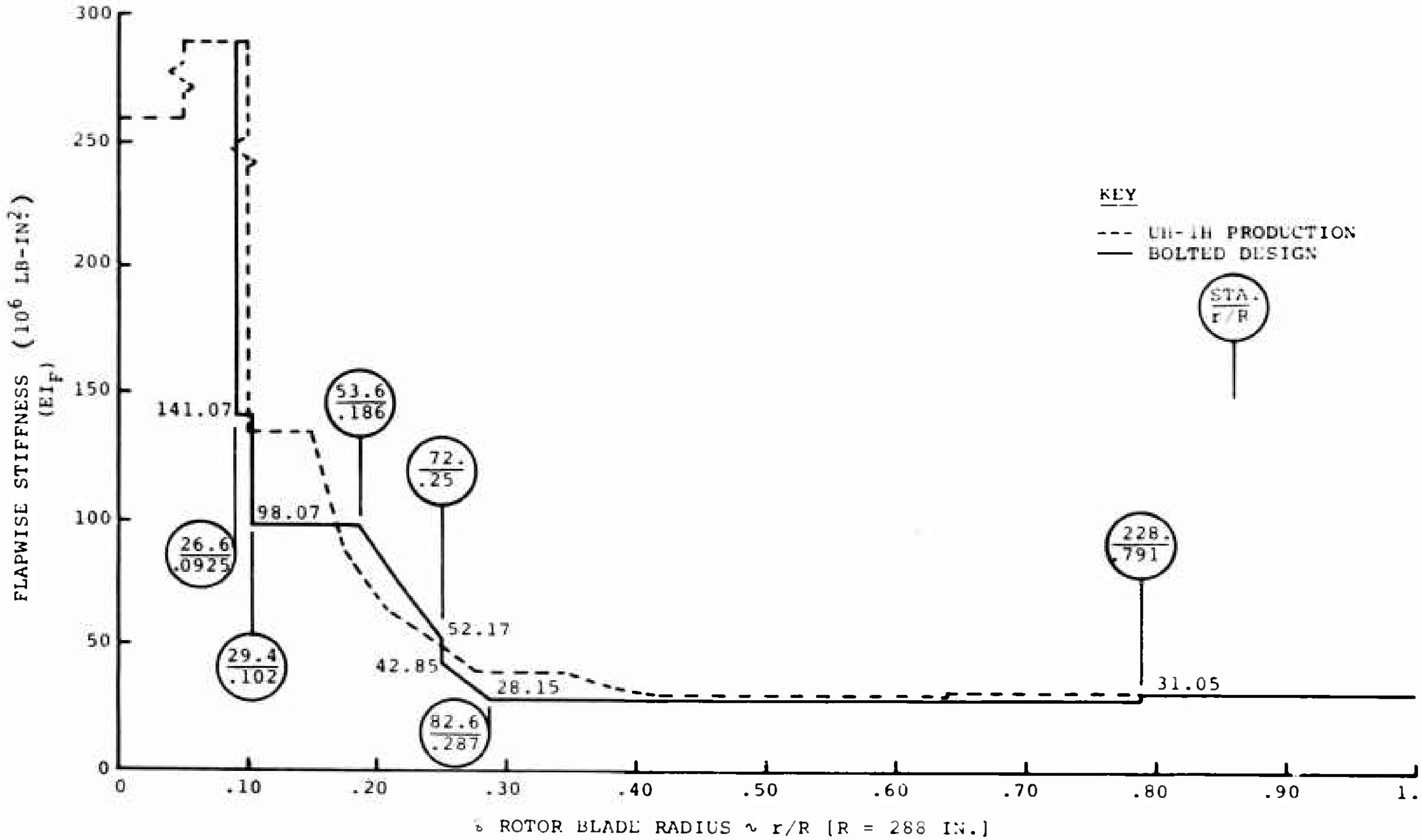


Figure 30. UH-1H Rotor Blade Flapwise Bending Stiffness.

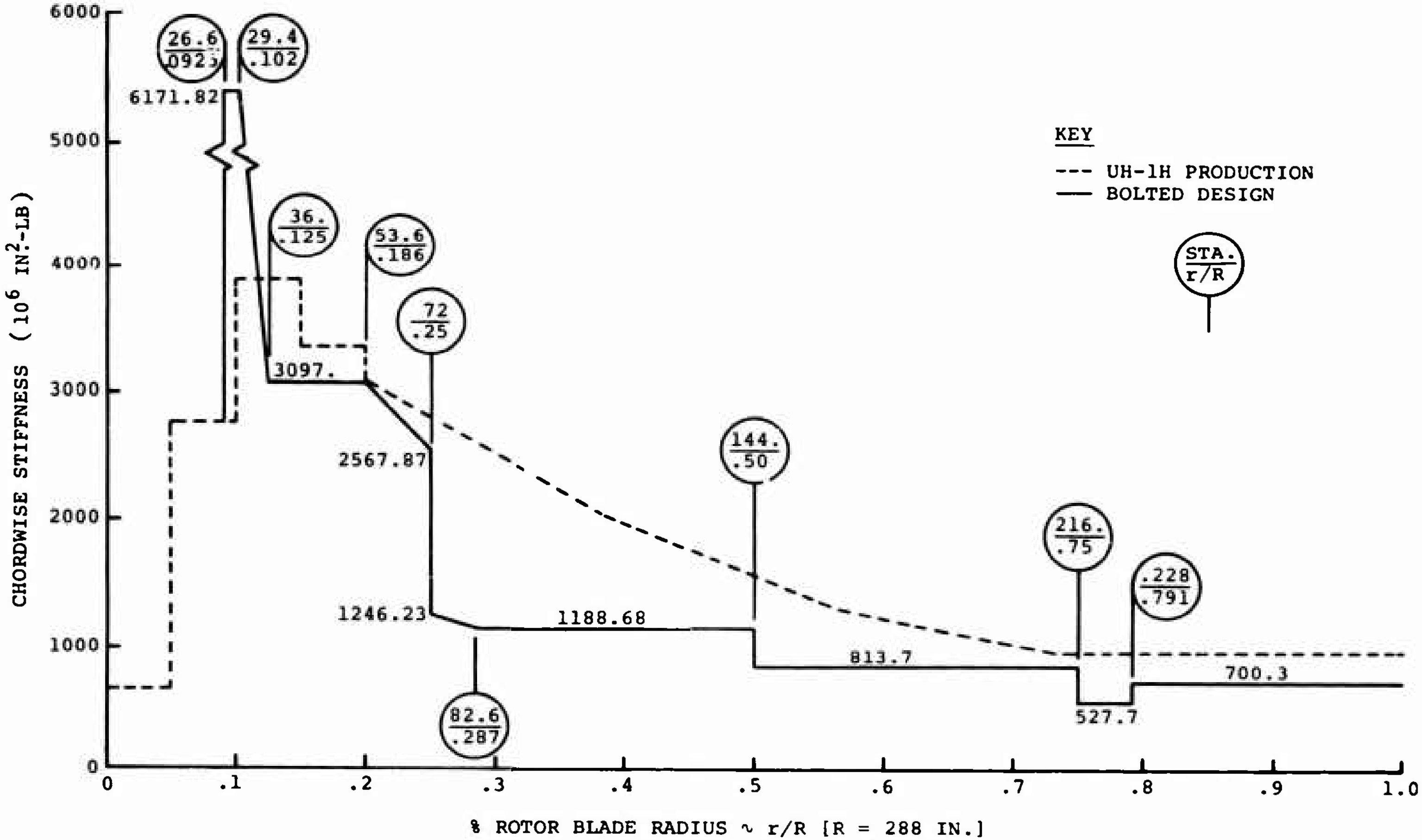


Figure 31. UH-1H Rotor Blade Chordwise Bending Stiffness.

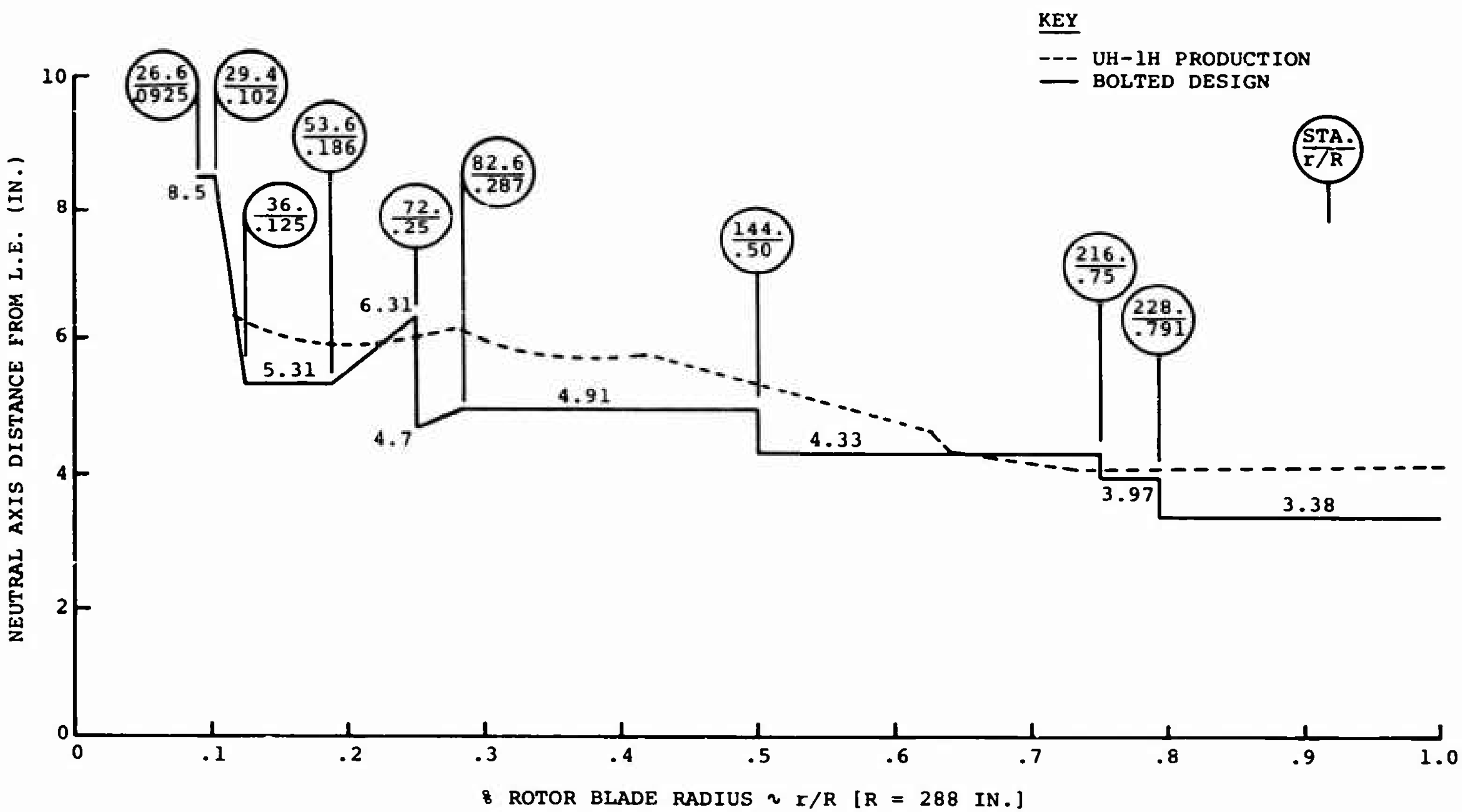


Figure 32. UH-1H Rotor Blade Chordwise Neutral Axis Location.

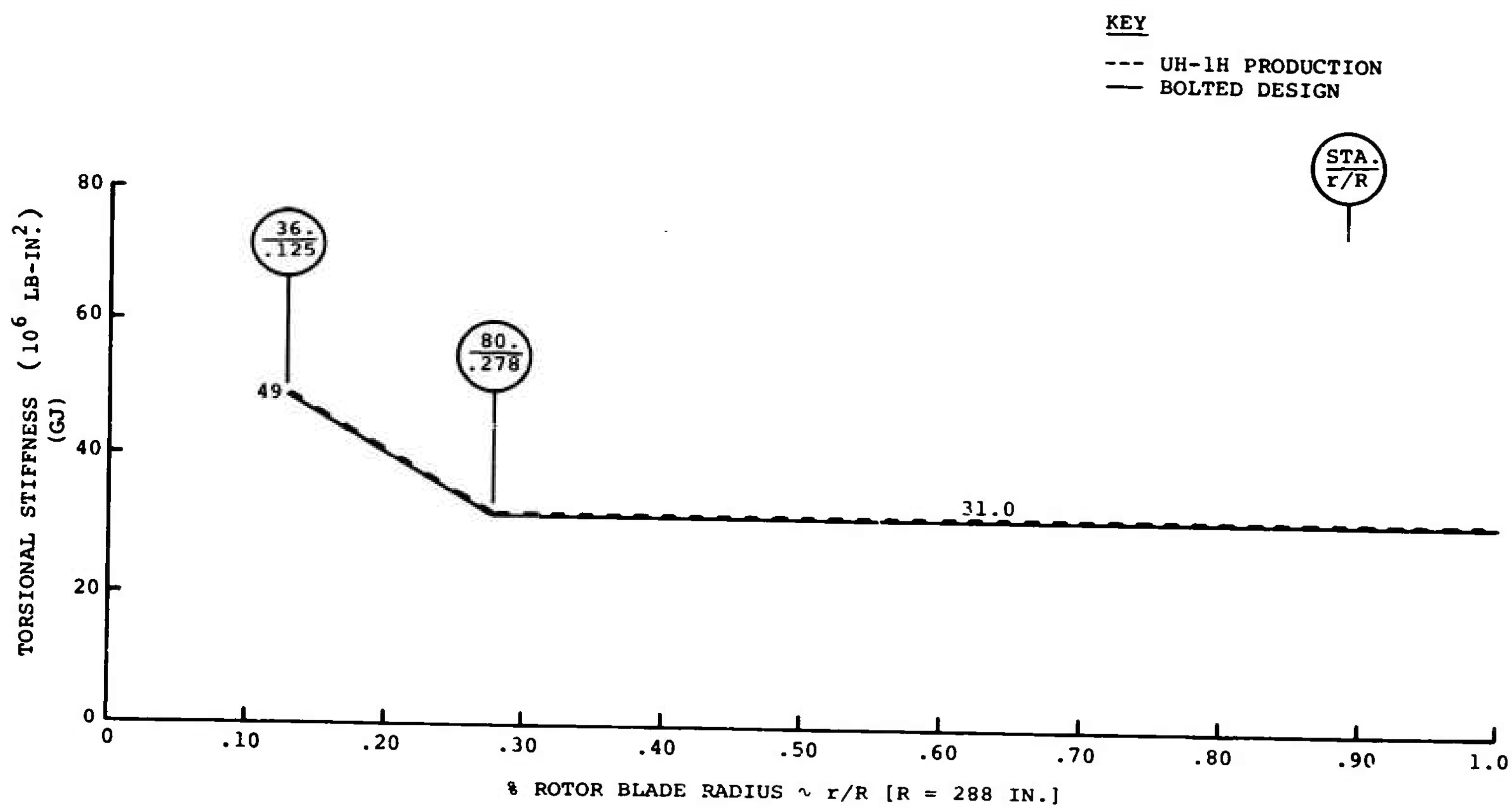


Figure 33. UH-1H Rotor Blade Torsional Stiffness Distribution.

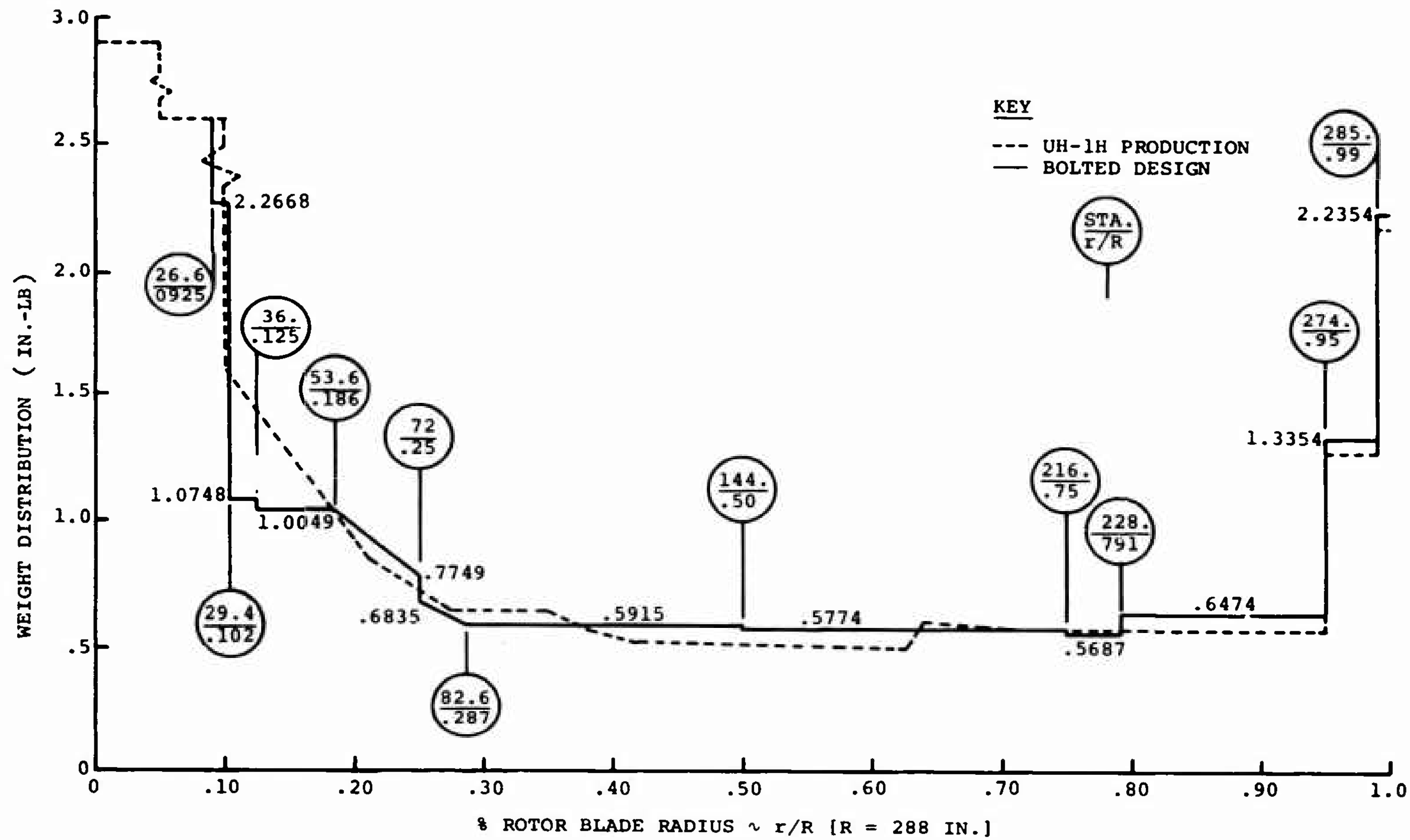


Figure 34. UH-1H Rotor Blade Spanwise Weight Distribution.

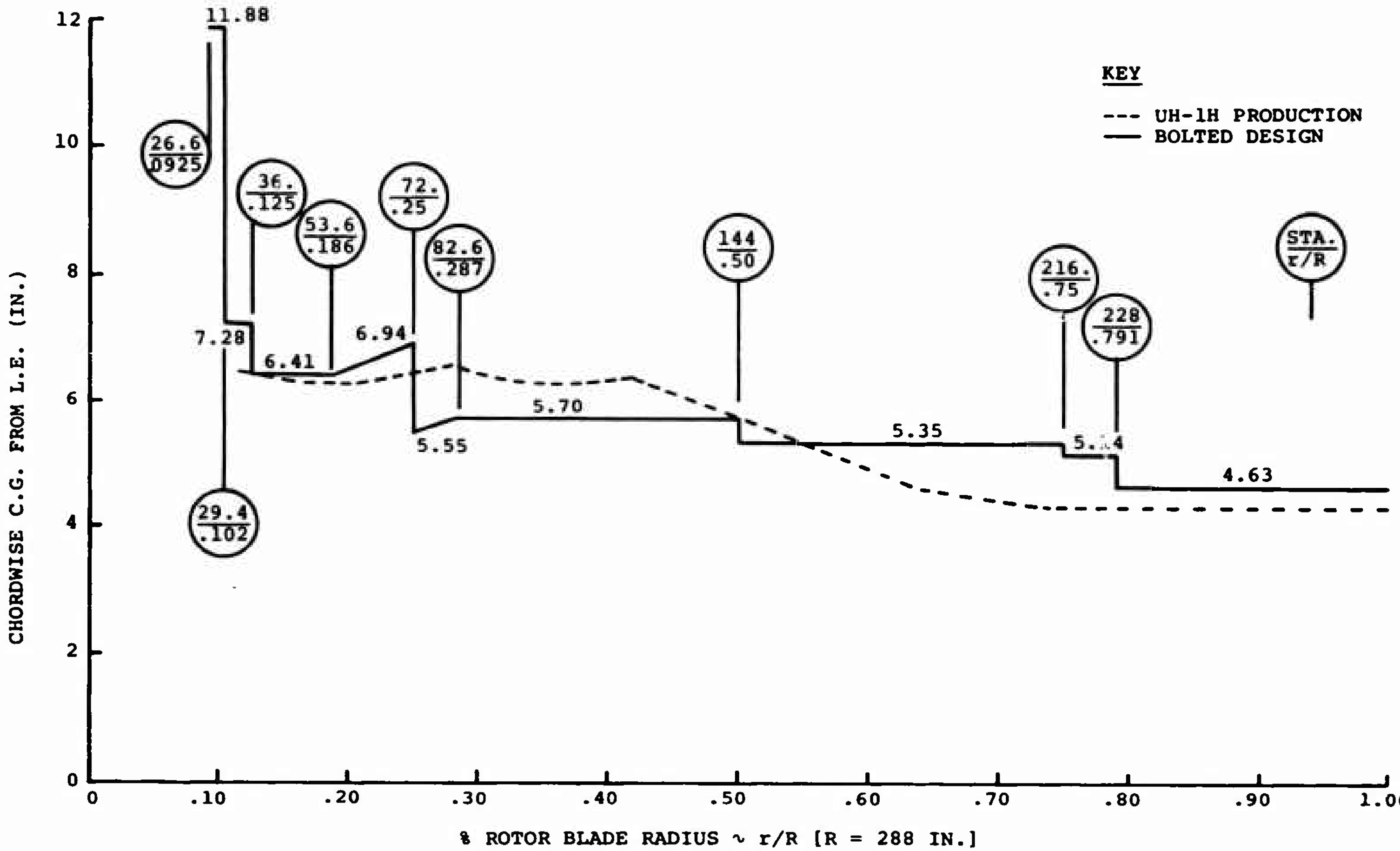


Figure 35. UH-1H Rotor Blade Spanwise Center of Gravity Distribution (Inches from Leading Edge).

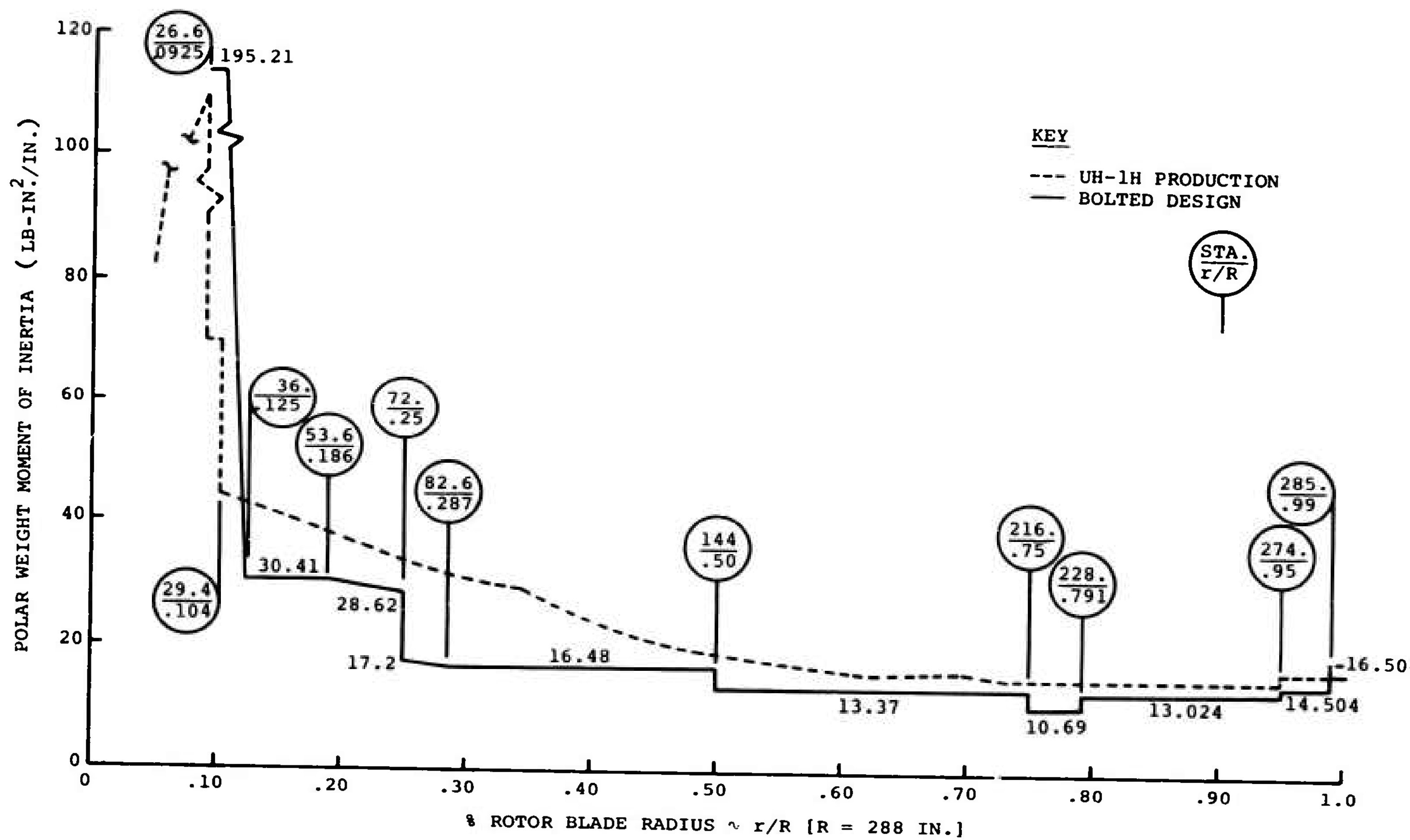


Figure 36. UH-1H Rotor Blade Polar Weight Moment of Inertia About the Pitch Axis.

inertia about the pitch axis for the bolted design is somewhat less than for the UH-1H production blade. This is a result of the reduction of weight of the boxes and the increase in weight on the spar.

3. Natural Frequency

Tables X and XI present the natural frequencies, related to RPM, for the pin-free mode, and the fixed-free mode of the rotor system. Each table contains the flap, chord, and torsion natural frequencies for the UH-1H production blade and the bolted design. There is very little difference in the flapwise mode between the two blades, but a noticeable difference in the chord and torsional modes. The first chord natural frequency (ω_n/Ω) in the fixed-free mode (Table XI) is closer to one per rev for the bolted design. This was the result of the chordwise stiffness reduction from the production design to the bolted design (see Figure 31).

4. Bending Moments

Figure 37 presents the steady flap bending moments, as calculated per computer program LO-2, for the production UH-1H rotor blade, and the bolted design sectionalized blade. The bolted design is somewhat higher inboard of 50% radius, but the only effect is a 900-psi increase in the spar steady stress at the critical station (Sta. 72, Ref. Bell UH-1H report 205-099-313, Pg. iv).

Figure 38 presents the steady chord bending moments for the two blades. The general distributions are the same; however, the steps in the trailing edge of the sectionalized blade are readily recognizable in the spanwise moment variations.

The steady torsional bending moments illustrated in Figure 39 indicate that the bolted design loads are lower in magnitude than that of the UH-1H production blade, due to the lower polar mass moment of inertia.

Figure 40 presents the comparative alternating flap bending moments for the two blades. There is very little difference between the two blades.

Figure 41 presents the relative alternating chord bending moments between the bolted design and the production UH-1H blade. The theoretical predictions of alternating chord bending moments are very dependent on the precise knowledge of root fixity. Not having the precise knowledge, the assumption of infinite root fixity was used for both blades and the results plotted on a comparative basis. This relationship was then applied to the measured UH-1H loads to obtain predicted loads

TABLE X. NATURAL FREQUENCIES (PIN-FREE MODE)

MODE	UH-1H Production Blade				Bolted Design Segmented Blade			
(RPM)	0/324	324	294	270	0/324	324	294	270
FLAP								
(0)	0.00	1.000	1.000	1.000	0.000	1.000	1.000	1.000
(1)	.72101	2.5764	2.5999	2.6240	.6725	2.5787	2.5994	2.6206
(2)	2.3925	4.5519	4.6921	4.8334	2.2986	4.5822	4.7131	4.8448
(3)	5.2359	7.6665	8.0528	8.4373	5.0352	7.5099	7.8746	8.2380
(4)	9.2228	11.845	12.603	13.352	8.7688	11.493	12.198	12.895
(5)	14.273	17.064	18.311		13.474	16.447	17.598	
CHORD								
(1)	4.9661	5.4779	5.9455	6.4003	3.9355	4.5497	4.9013	5.2456
(2)	14.466	15.205	16.674	18.090	12.487	13.046	14.271	15.454
TORSION*								
(1)	4.6508	4.7225			5.1709	5.4302		
(2)	10.533	10.553			10.768	10.816		

* @ $K = 1.84 \times 10^6$

TABLE XI. NATURAL FREQUENCIES (FIXED-FREE MODE)

MODE	UH-1H Production Blade				Bolted Design Segmented Blade			
(RPM)	0 / 324	324	294	270	0 / 324	324	294	270
FLAP								
(0)	0.23943	1.1611	1.1729	1.1839	0.22184	1.1538	1.1649	1.175
(1)	1.4832	3.2205	3.3008	3.3812	1.3966	3.1691	3.2423	3.3156
(2)	3.9355	6.0451	6.3258	6.6049	3.7406	5.9811	6.2384	6.495
(3)	7.4108	9.7820	10.379	10.968	7.0188	9.5665	10.119	10.67
(4)	11.632	14.112	15.117	16.102	11.260	13.921	14.881	15.82
(5)	16.733				16.281			
CHORD								
(1)	1.1653	1.2153	1.3304	1.4413	1.0313	1.1107	1.2104	1.307
(2)	6.4954	6.9187	7.5445	8.1506	5.4916	5.9900	6.5075	7.011
TORSION*								
(1)	4.6508	4.7225			5.1709	5.4302		
(2)	10.5325	10.553			10.768	10.817		

* @ $K = 1.84 \times 10^6$

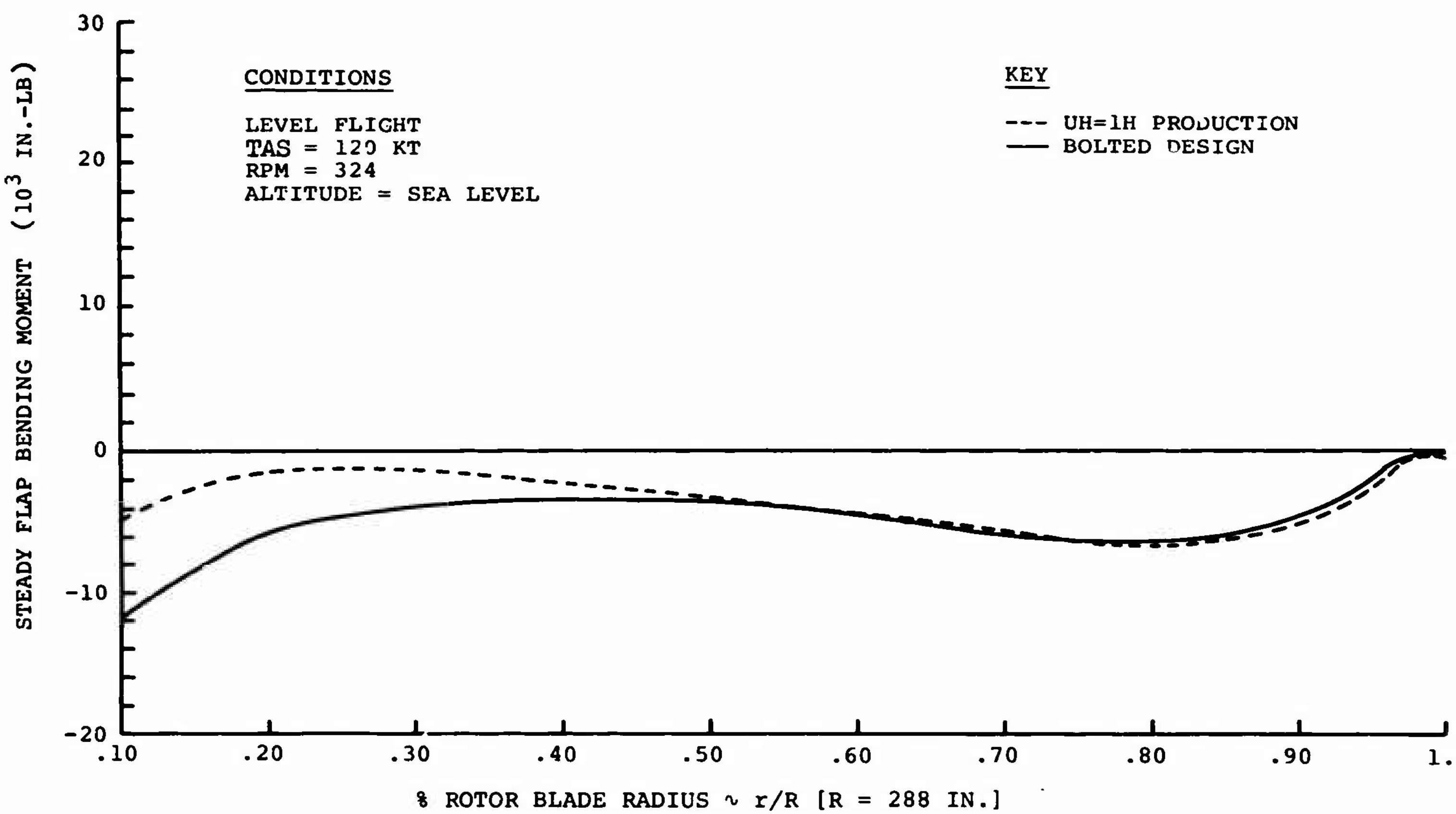


Figure 37. UH-1H Rotor Blade Steady Flap Bending Moment Distribution.

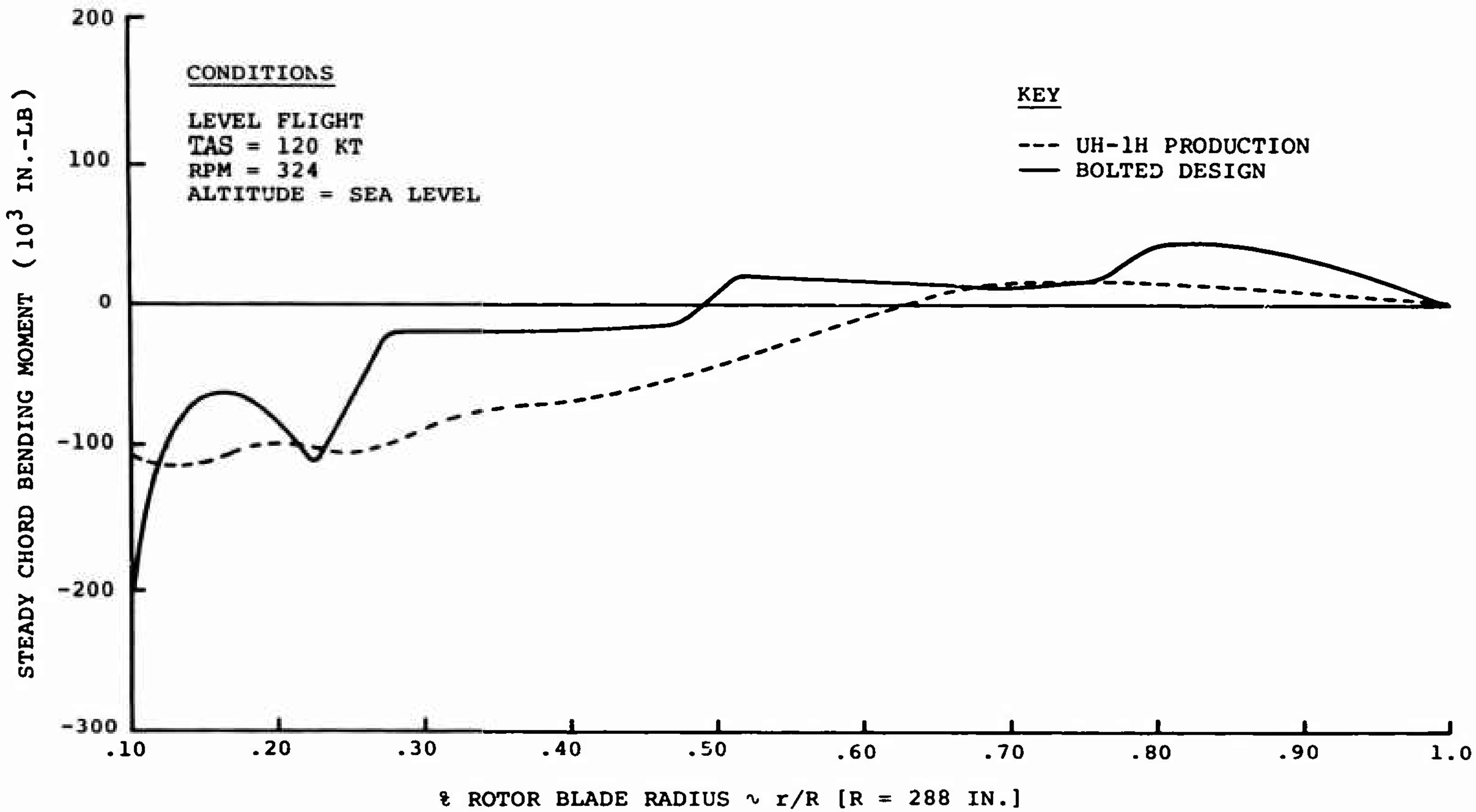


Figure 38. UH-1H Rotor Blade Steady Chordwise Bending Moment Distribution.

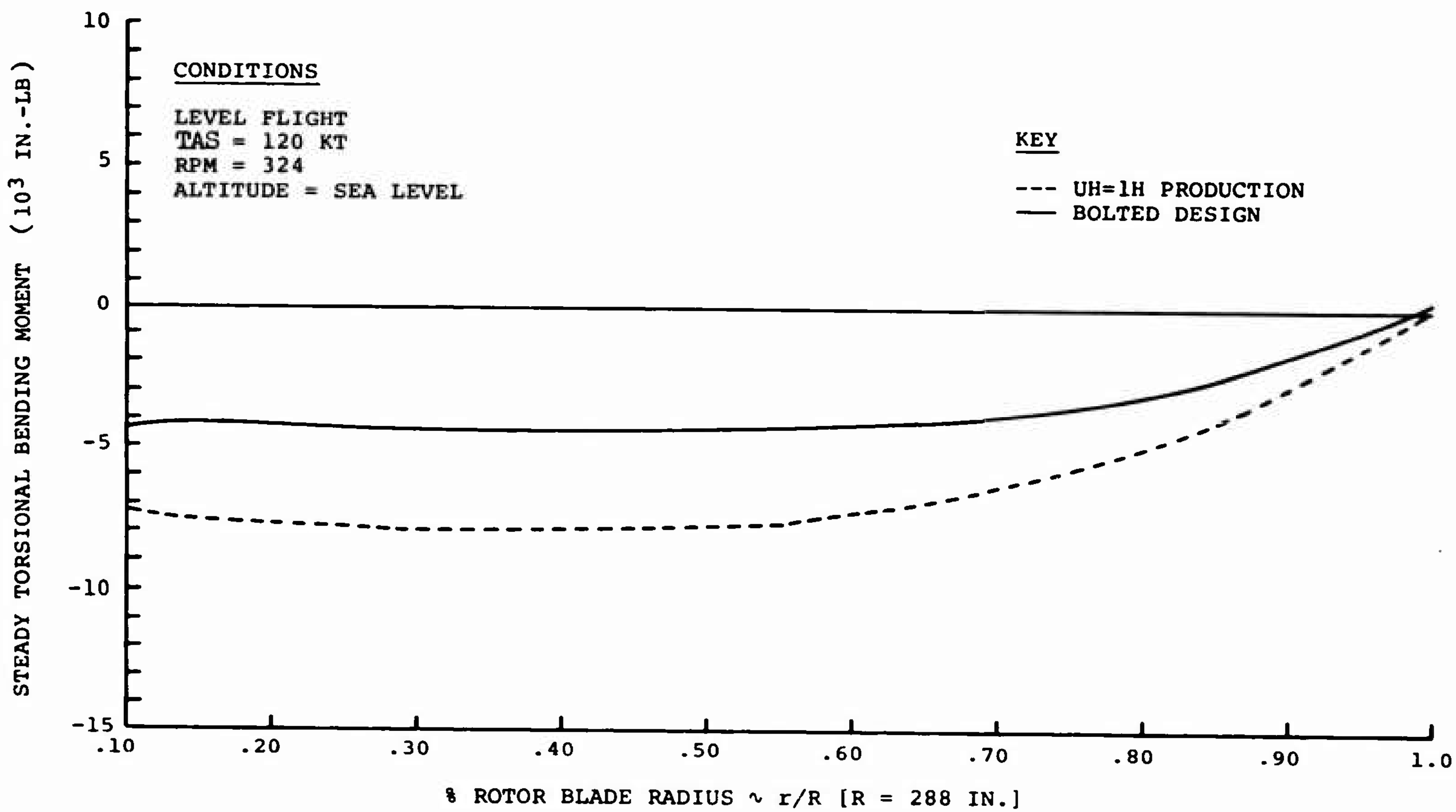


Figure 39. UH-1H Rotor Blade Steady Torsional Bending Moment Distribution.

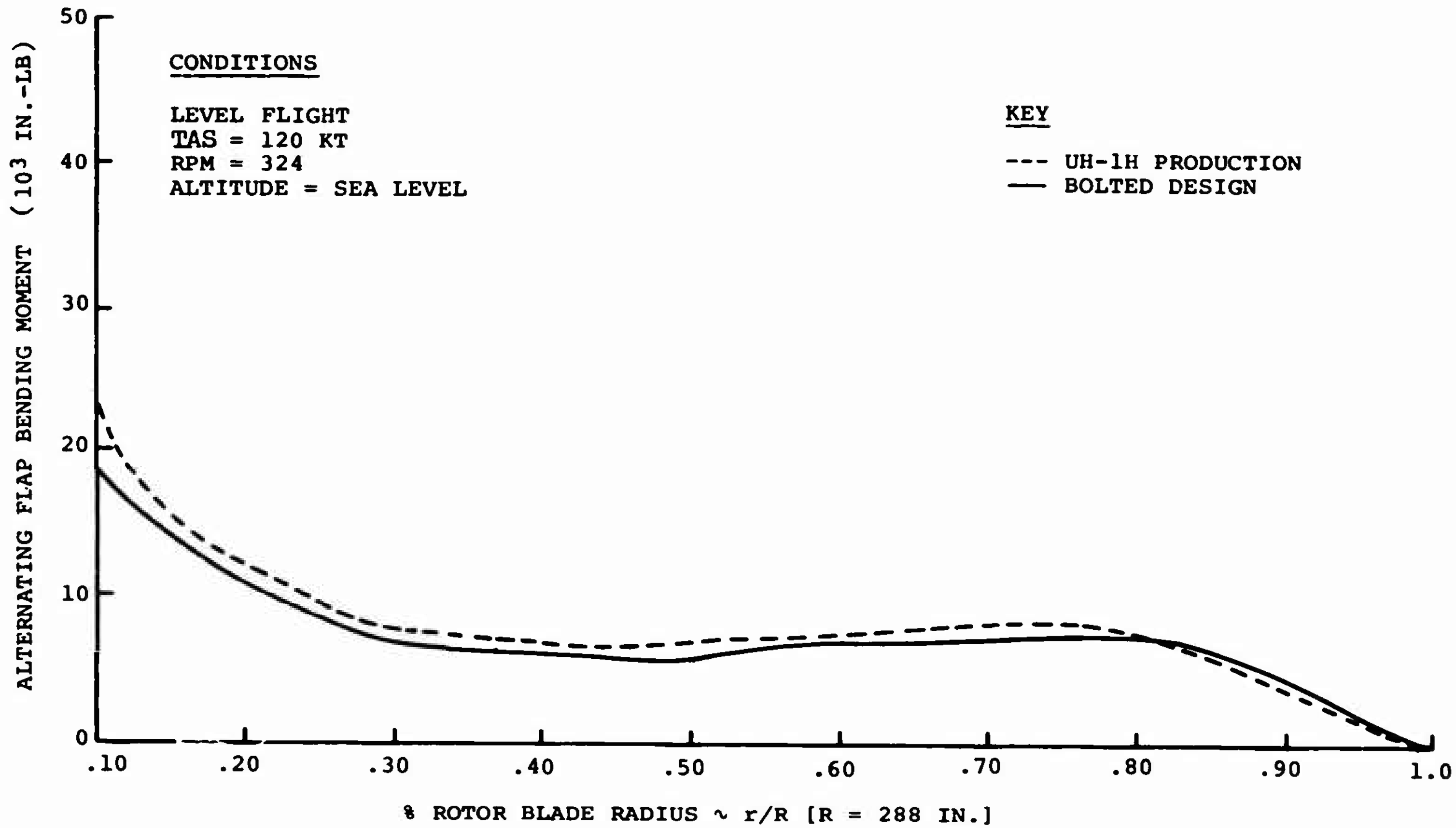


Figure 40. UH-1H Rotor Blade Alternating Flap Bending Moment Distribution.

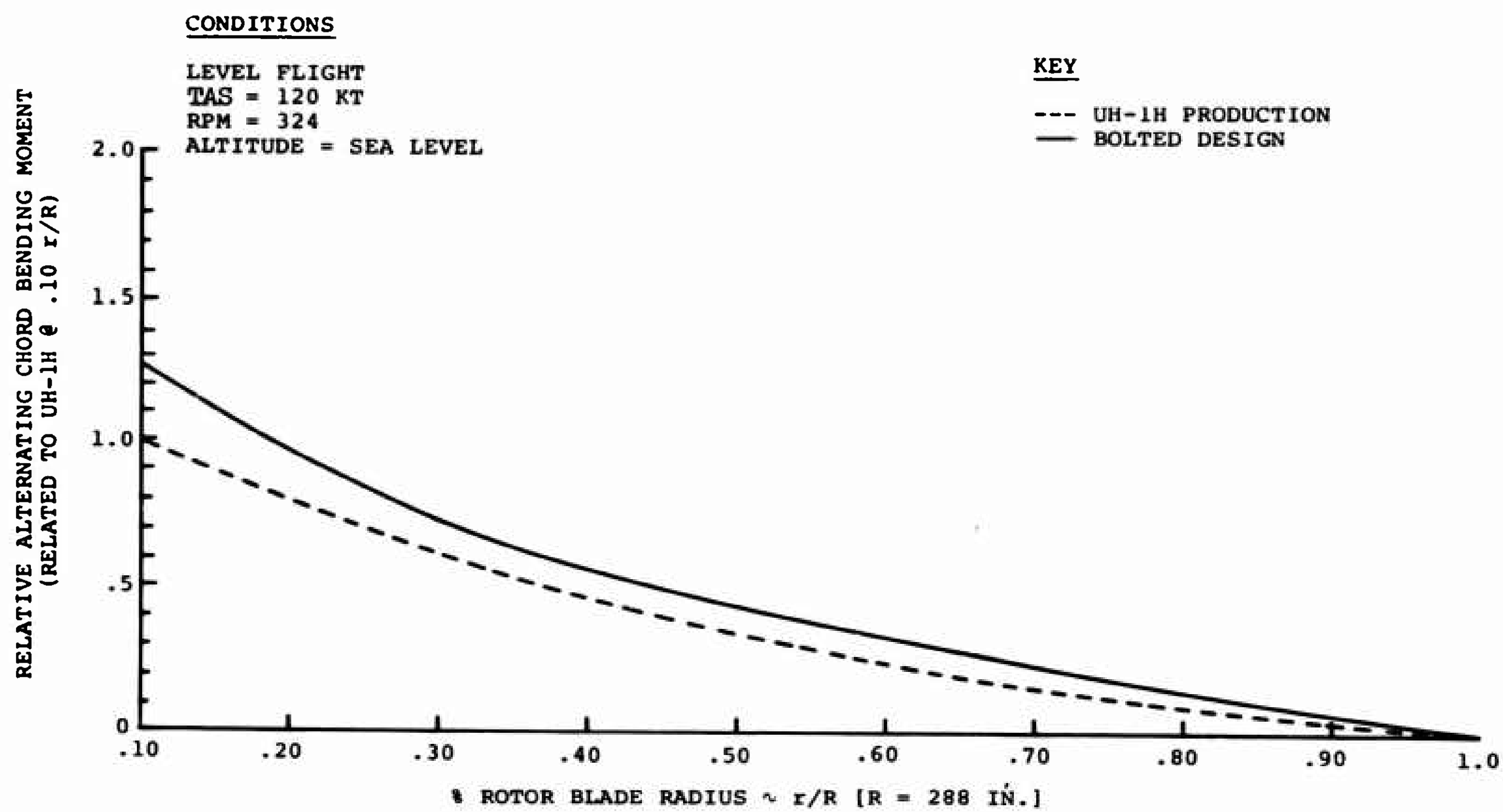


Figure 41. UH-1H Rotor Blade Relative Alternating Chord Bending Moment Distribution.

for the sectionalized blade. The higher chord moments are attributed to the nearness of the first chord frequency to 1/rev.

The alternating torsional bending moments are shown in Figure 42. While the sectionalized bolted design loads are larger in magnitude than that of the production UH-1H blade, the increase is not appreciable.

5. Dynamic Balance Axis

   a. UH-1H Production Blade = 23.3%

   b. Bolted Design Blade = 24.23%

Dynamic Comparison

Figures 43 through 46 present a dynamic comparison of selected design arrangements.

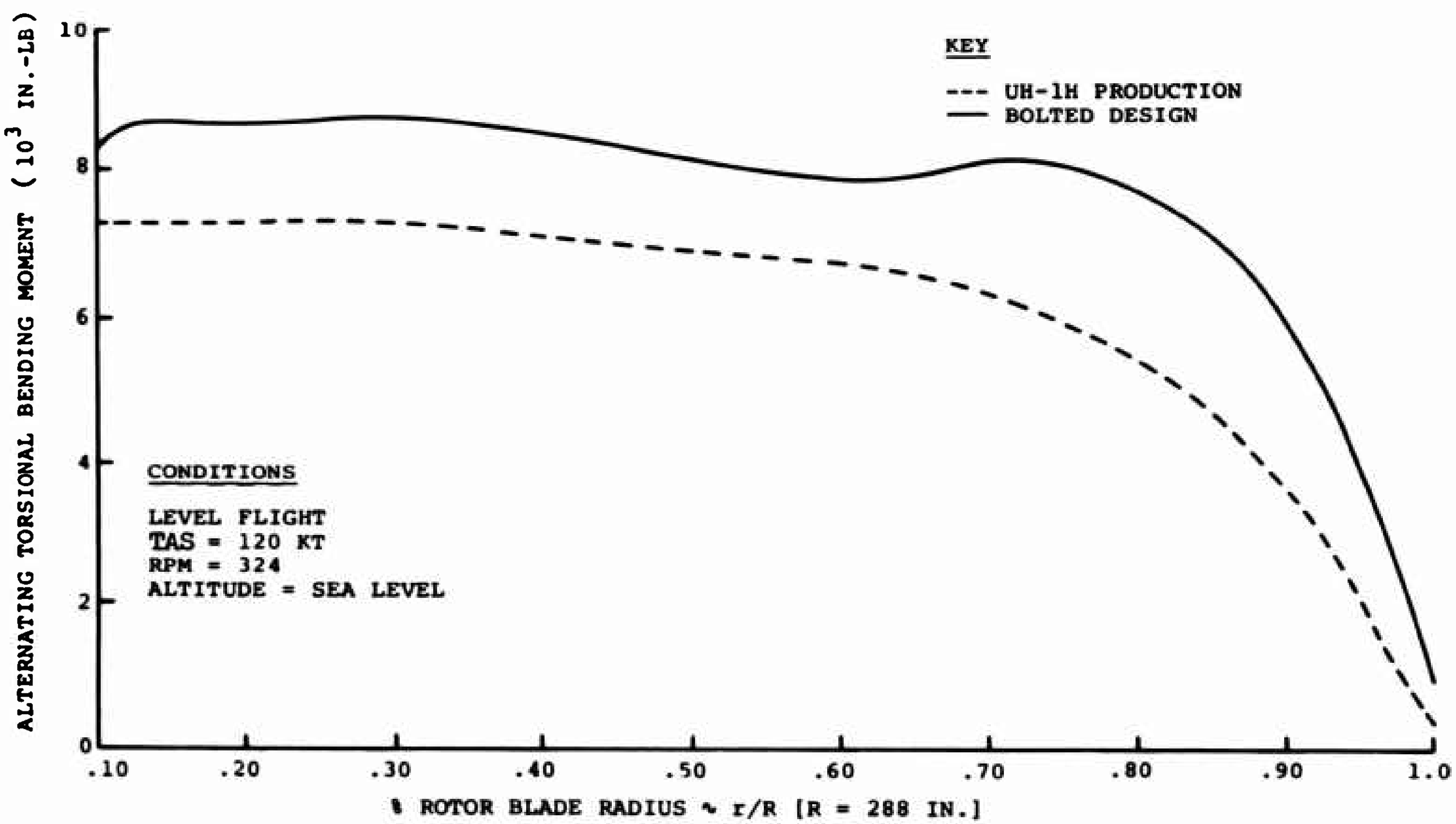


Figure 42. UH-1H Rotor Blade Alternating Torsional Bending Moment Distribution.

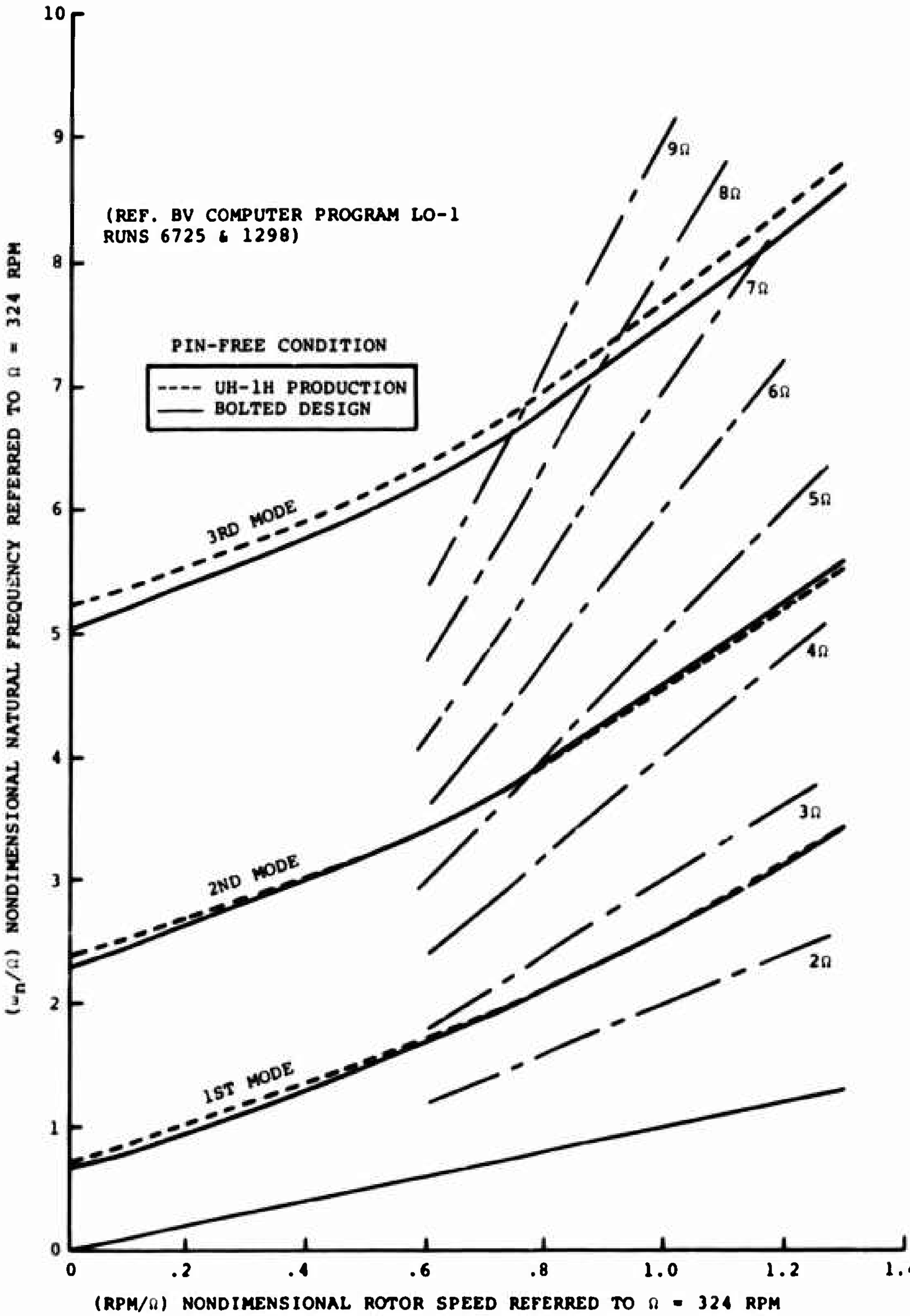


Figure 43. Uncoupled Flapwise Normal Modes for UH-1H (Production) Sectionalized Rotor Blades - Variation of Natural Frequency With Rotor Speed.

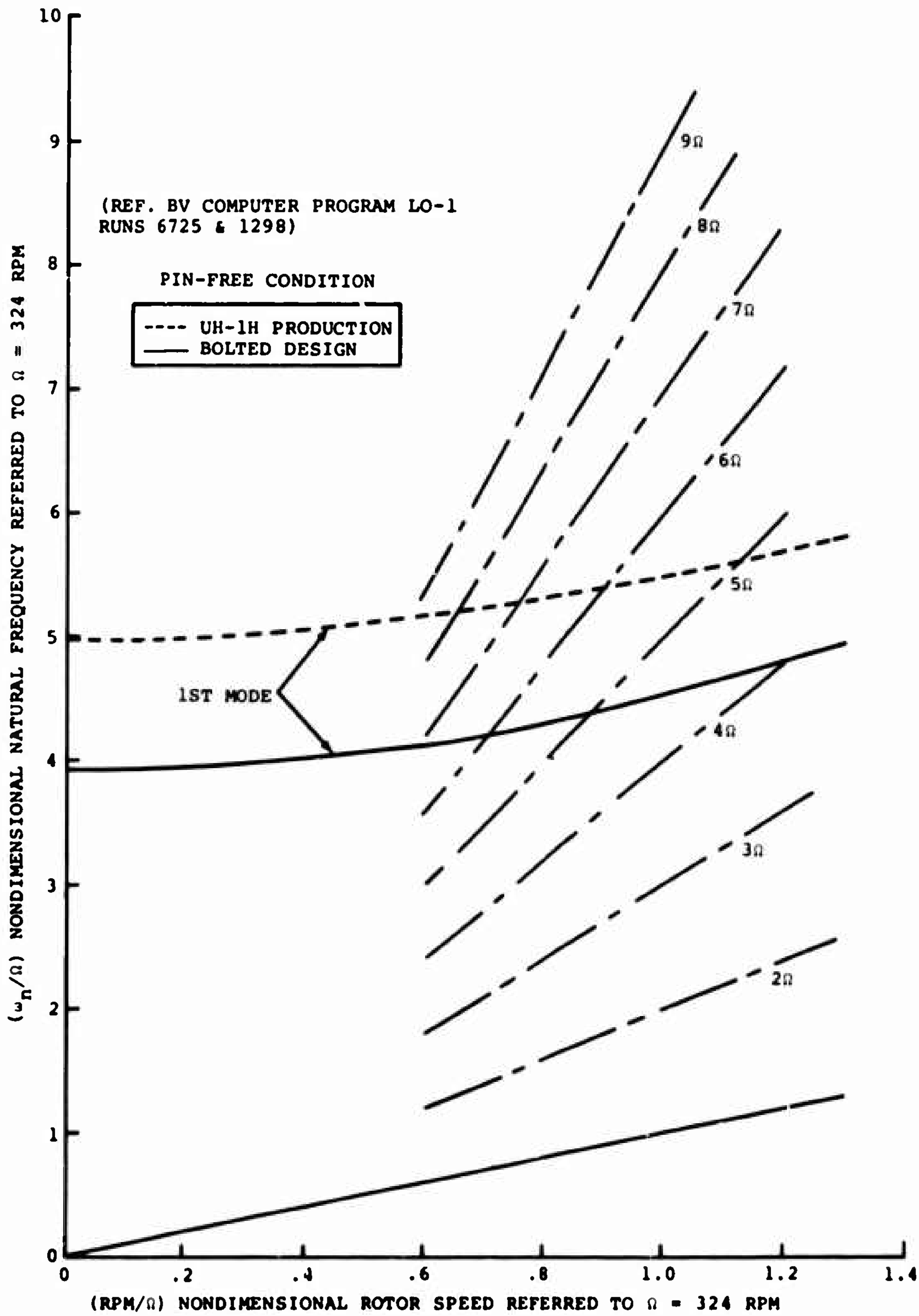


Figure 44. Uncoupled Chordwise Normal Modes for UH-1H (Production) Sectionalized Rotor Blades - Variation of Natural Frequency With Rotor Speed for Pin-Free Condition.

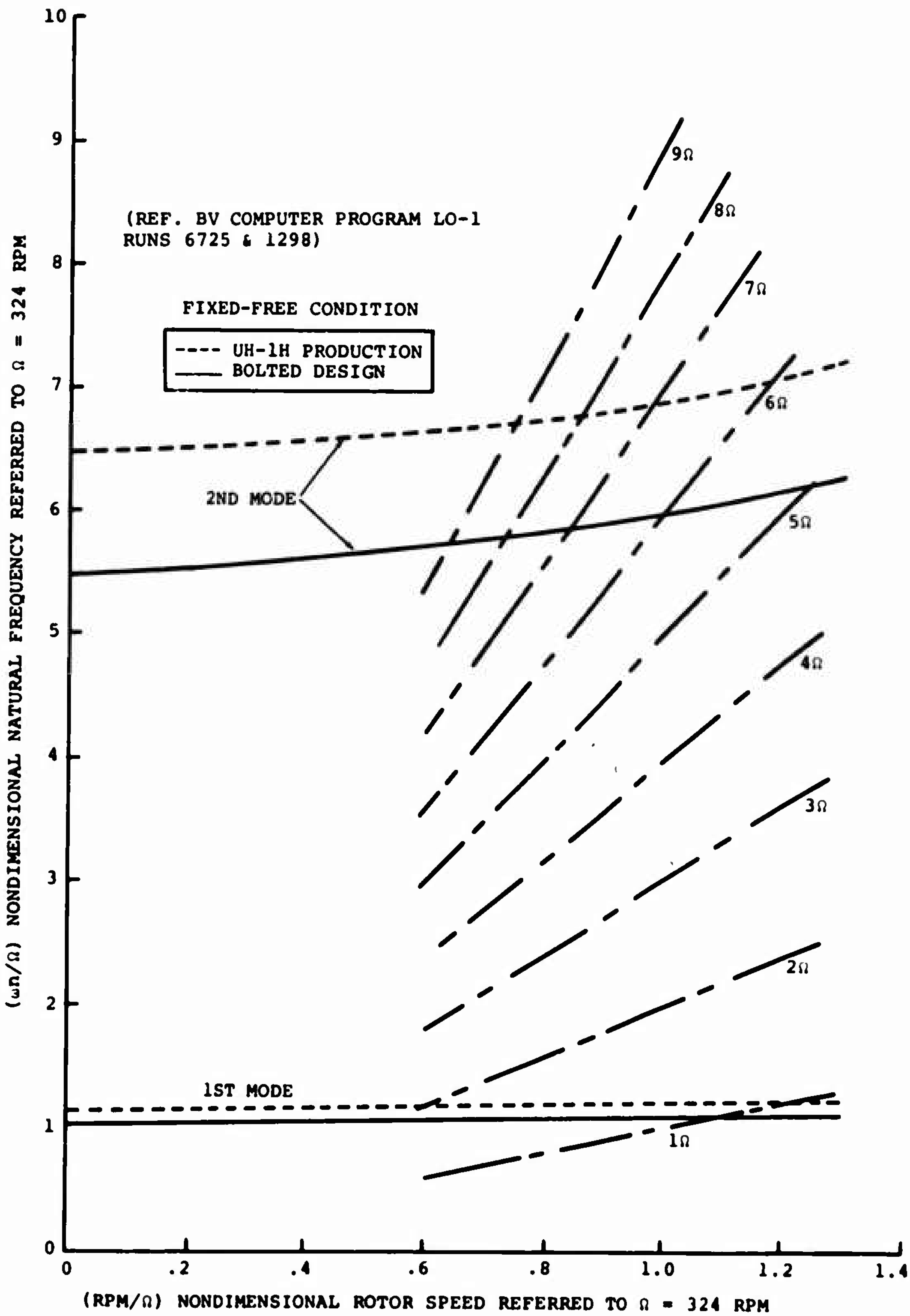


Figure 45. Uncoupled Chordwise Normal Modes for UH-1H (Production) Sectionalized Rotor Blades - Variation of Natural Frequency With Rotor Speed for Fixed-Free Condition.

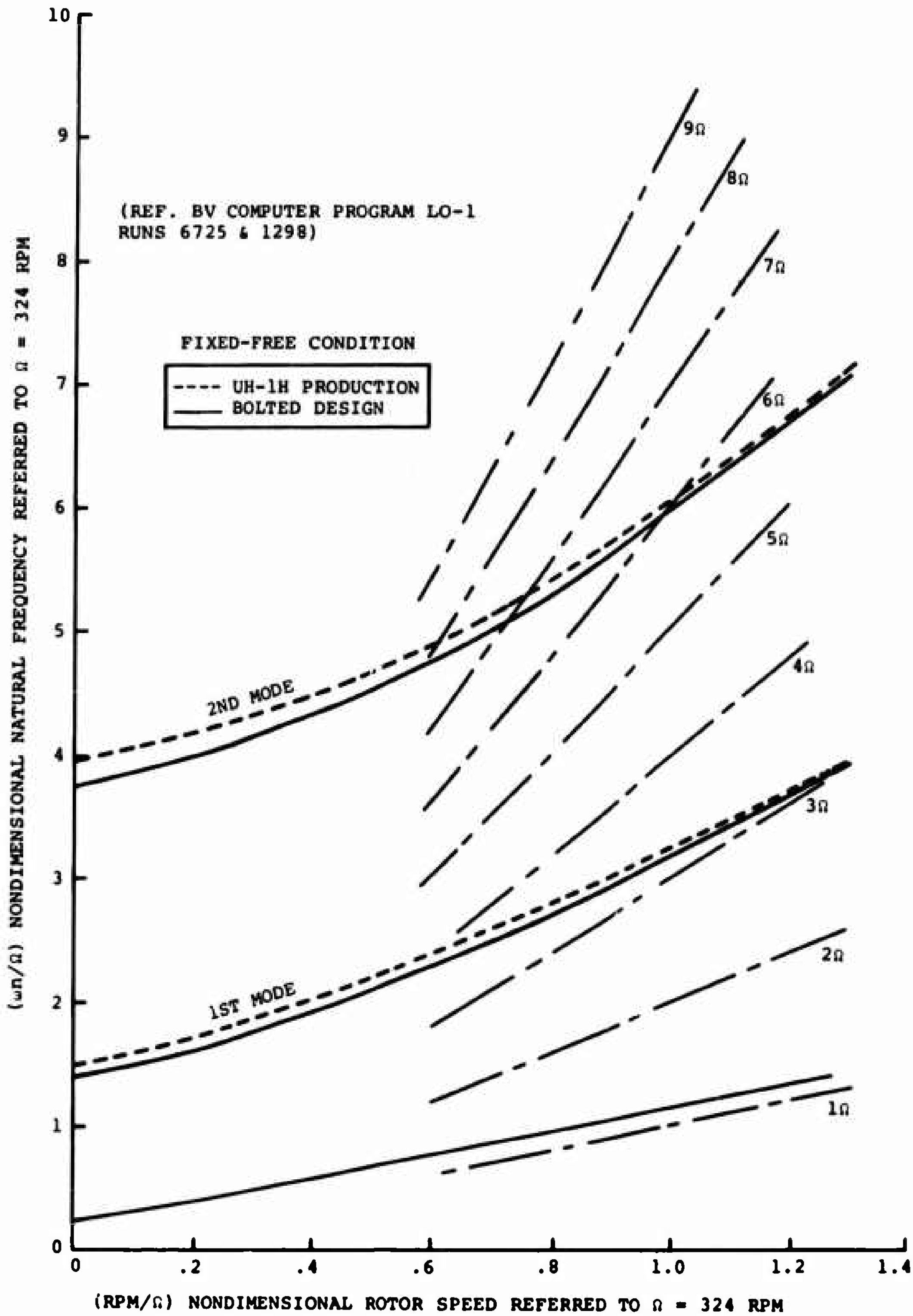


Figure 46. Uncoupled Flapwise Normal Modes for UH-1H (Production) Sectionalized Rotor Blades - Variation of Natural Frequency With Rotor Speed.

CONCLUSIONS

The following conclusions were reached at the completion of the Sectionalized Main Rotor Blade Advanced Design Study:

1. The sectionalized blade can be designed and manufactured using present-day technology.

2. Coupon and component tests must confirm some assumptions which were made in the absence of technical data.

3. The concept of the sectionalized blade is more readily adaptable to the soft- rather than the rigid-in-plane-of-rotation blade.

4. Repair of external damage to a sectionalized blade on the aircraft is feasible.

RECOMMENDATIONS

The first steps to be taken in further studies of the sectionalized blade, Figure 18, are:

1. Increase the basic knowledge of bolted joints in FRP structures

2. Verify the effectiveness of the energy-absorbing removable leading-edge portion

The study of the behavior of the leading-edge member under the impact of a solid object, such as a tree branch, will require manufacture of components representing the configuration of the front portion of the spar and the leading-edge member. The assembly of these two components should be subjected to the impact (the magnitude to be defined) which will determine the extent of damage (if any) to the spar and the spanwise spread of deformation of the leading-edge member. If this deformation (i.e., opening of V-shaped leading-edge member) is spread over a large portion of the blade radius, it will act as a spoiler which could change considerably the flying characteristics of the aircraft. In this case, sectionalizing of the leading-edge member into several spanwise components would be recommended.

APPENDIX
DEVELOPMENT OF THE PLAN FOR FUTURE HARDWARE EVALUATION

The following factors will be considered in development of the plan for future evaluation of hardware for the sectionalized main rotor blade:

1. Development of the preliminary design specification
2. Evaluation for operational suitability
3. Design plus tooling and manufacture of four (4) blades
4. Laboratory tests of blade sections and complete assemblies
5. Whirl tests
6. Flight tests

DEVELOPMENT OF PRELIMINARY DESIGN SPECIFICATION

This effort will encompass the design criteria (weight, droop, natural frequencies, etc.) which will necessarily deviate slightly from those of the UH-1H rotor blade. Of special importance will be the first mode of in-plane frequency.

OPERATIONAL SUITABILITY EVALUATIONS

The proposed sectionalized rotor blade concept shall be evaluated for operational suitability by performing the following Reliability and Maintainability program.

1. Provide flight test vehicle and test facilities in varying climatic conditions (i.e., hot and humid, hot and dry, cold, etc.).
2. Perform accellerated flight test program (150 hr/mo until 2,000 hours) using U.S. Army crews performing simulated tactical missions.
3. Provide GSE, publications and training to meet the maintenance concept.
4. Introduce simulated battle damage and monitor inherent damage.
5. Monitor test program and compare results to predicted values.

DESIGN

The design will be based on the Sectionalized Blade (Bolted Version) in accordance with Boeing-Vertol drawing No. 168-10100.

BLADE SECTION AND COMPLETE ASSEMBLY LABORATORY TESTS

This program is described in detail below. Of particular importance is the element test program since its results may affect the final blade arrangement.

There is a lack of reliable information concerning the fatigue properties of bolted joints in Fiberglass-Reinforced-Plastics (FRP). This information is essential for the development of the proposed blade.

The following tests will be performed in this program:

1. Single lap-bolted specimens fatigue test
2. Trailing-edge box ultimate and fatigue test
3. Static blade deflection test to determine flapwise, chordwise, and torsional section moduli
4. Static blade trailing-edge buckling test
5. Static blade tip pull test
6. Nonrotating natural frequency tests
7. Bench fatigue test of spar-to-box joint (high load, low temperature)
8. Bench fatigue test of blade root end with steady axial load, combined flap and chord bending, and torque (including simulated centrifugal-force proof test)
9. Bench fatigue test of blade intermediate section with axial load and combined bending
10. Bench fatigue test of blade outboard section with axial load and combined bending

Single Lap-Bolted Specimens Fatigue Test

This test will consist of the fatigue test of specimens similar to those tested by the McDonnell Douglas Company under USAF Contract F33615-67-1582 and described in the report, INVESTIGATION OF JOINTS IN ADVANCED FIBROUS COMPONENTS FOR AIRCRAFT STRUCTURES.

Forty specimens will be divided into two groups, a screening group and an S/N group. The first group will evaluate the effect of several variables on specimen configuration:

1. Cloth in 0-90-degree layup
2. Cloth in 45-45-degree layup
3. Snug fit between hole and bolt
4. Loose fit between hole and bolt
5. Sloppy fit - potted hole
6. 2 ft-lb torque exerted on the nut
7. 5 ft-lb torque exerted on the nut
8. Countersunk hole for the head of the bolt
9. Countersunk hole protected by dimpled washer
10. Edge distance 0.48 inch and 0.38 inch (in upper and lower panel respectively)
11. Edge distance decreased (or increased) by 0.060 inch, depending on the result of preceding

All specimens will be single-lap, single-bolt (10 countersunk machine screw) joints in 0.22-inch-thick panels.

The test objectives are set forth in the test matrix shown below.

TEST MATRIX - SINGLE LAP-BOLTED SPECIMENS

NUMBER OF SPECIMENS TO BE TESTED	a	b	c	d	e	f	g	h	i	j	k
4	X		X			X		X		X	
4		X	X			X		X		X	
4	X*		X			X		X			X
4	X			X		X		X		X*	
4	X				X	X		X		X	
4	X			X*			X	X		X	
4	X			X		X*		X		X	
4	X			X		X			X	X	
4	Reserved for additional configuration										

CONFIGURATION DEFINITION columns a–k.

*Best of the group

The results will be evaluated against the preferred configuration (proposed in the sectionalized blade study) which consists of 45-degree oriented fabric (0.22 inch panel thickness), single lap-bolted joint achieved by No. 10 countersunk machine screw, torqued to 2 ft-lb, with edge distance of 0.48 inch in countersunk panel and 0.38 inch in the drilled-only panel.

Thirty-six specimens will be tested in the screening group. The remaining group of 4 will be used to determine a preliminary S/N curve for the most desirable configuration resulting from the screening test. This group of 4 points, added to the 4 screening test points, yields a total of 8 points for the S/N curve.

Trailing-Edge Box Ultimate and Fatigue Test

Upon completion of the first tests, which will evaluate the structural soundness of the spar-to-box bolted joint, the second test will be initiated. If any changes in design are found necessary as a result of the bolted-joint tests, they will be incorporated in the design of the trailing-edge box and tooling for the box ordered. This procedure will eliminate the risk of premature tool fabrication and subsequent modification.

Nine trailing-edge boxes will be manufactured using the Vacuum-Pressure Injection (VPI) method.

These boxes will be subjected to static and fatigue tests either in full width (12 inches wide featuring 7 ribs) or cut into 2-rib-wide or 1-rib-wide specimens. Two trailing-edge boxes will be cut, yielding five 2-rib-wide and four 1-rib-wide specimens. The specific test objectives are described in the following paragraphs.

Simulated Airload Ultimate Strength Test

One 2-rib-wide specimen will be tested under simulated airload, the magnitude of which will be such that it will produce the calculated shear and bending at the bolted connection of the box.

Airload Fatigue Test

Four 2-rib-wide specimens will be tested under steady and alternating simulated airloads.

Chordwise Load Fatigue Test

Four 1-rib-wide specimens will be tested under steady and alternating load applied to the trailing edge of the specimens and acting in the plane of the chord.

Fatigue Inflation Test

Two full-size trailing-edge boxes will be tested under simulated negative pressure loads.

Airload Fatigue Test of Trailing-Edge Box

Two full-size trailing-edge boxes will be tested under steady and alternating simulated airloads.

Edgewise Fatigue Test of Trailing-Edge Box

Four full-size trailing-edge boxes will be tested under steady and alternating loads acting in the plane of the chord and applied to the trailing-edge member.

Static Blade Deflection Test to Determine Section Moduli

The purpose of this test is to determine the chordwise, flapwise, and torsional section moduli of one sectionalized main rotor blade assembly at approximately five spanwise blade stations.

The test specimen will be one full-length blade assembly; this same blade will be cut into sections and used for bench fatigue tests described elsewhere in this report.

The blade will be mounted as a cantilever beam to represent a typical aircraft installation. Bending moments will be applied to the blade by suspending weight from a profiled clamping fixture attached near the outboard end of the blade.

Determination of Flapwise Section Moduli

The chord reference line at the station to be evaluated will be set horizontal in the flap-bend-down position and a dead weight will be applied at the outboard end of the blade at the theoretical chordwise neutral axis. Strain-gage outputs at several peripheral locations around the station being evaluated will be recorded, together with blade deflections.

Determination of Chordwise Section Moduli

The chord reference line at the station to be evaluated will be set vertically in the nose-up position and a load will be applied at the outboard end of the blade at the theoretical chordwise neutral axis. Strain-gage outputs at several peripheral locations around the station being evaluated will be recorded, together with blade deflections.

The neutral-axis locations will be determined by geometric analysis of strain-gage outputs and EI values will be determined from the flexure formula $\varepsilon = \frac{MC}{EI}$. The applied bending moments (M) at the various gage locations will be derived by geometric and load values.

Determination of Torsional Properties

To determine the torsional section moduli, torque will be applied to the tip of the blade and the angular twist will be measured at several spanwise stations.

To locate the shear center, the point of application of a shear load will be varied at the blade station being evaluated until the position is found where the flap and chord axes maintain their relative positions as the blade deflects. This will locate the position of true shear center.

Static Blade Trailing-Edge Buckling Test

The purpose of this test is to determine the chordwise bending moment capacity of the sectionalized main rotor blade. The test specimen will be one full-length sectionalized rotor blade assembly, which will also be used for the deflection tests. Strain gages will be positioned on the trailing edge and at other critical locations.

The blade will be mounted as a cantilever beam with the chord reference line vertical and the trailing edge in compression. Bending moments will be applied to the blade by suspending dead weight from a profiled clamping fixture attached at the outboard end of the blade. The load will be applied in five increments up to the trailing-edge design compression load. If trailing-edge buckling is visible during load application, the load will be released to check if buckling is permanent. Strain-gage output will be recorded at each load increment.

Static Blade Tip Pull Test

The purpose of this test is to determine the static ultimate strength of the tip weight fittings. The test specimen will be one tip section cut from the end of the blade. This section will include all associated tip hardware.

The inboard end of the blade section will be fastened to a support to react the applied longitudinal loads. Load will be applied by a whiffletree beam arrangement; individual stud loads will be monitored by calibrated load links. The longitudinal load will be applied incrementally until ultimate failure.

Nonrotating Natural Frequency Tests

The purpose of this test is to determine the nonrotating natural frequencies and mode shapes of a full-length sectionalized main rotor blade in the flapwise, chordwise, and torsional directions.

The test specimen will be one full-length blade assembly.

The test specimen will be mounted as a cantilever beam with the inboard end held rigidly in a test fixture. The blade will be oriented with the trailing edge up for all three test directions. During the flapwise and chordwise vibration, a bungee cord will support the blade at the extreme outboard nodal point of the particular mode being excited. For the torsional vibration the blade will be supported at the tip by a clamp and steel cables.

Induced vibration forces will be monitored with a strain-gaged load ring located between the shaker and the blade and a miniature lightweight accelerometer will be used to probe blade excitations. An accelerometer will also be mounted on the blade in line with the induced vibration location to monitor resonant conditions.

Flapwise Frequency Test

Vibration forces will be induced from the vertical direction at the inboard end of the blade. A frequency sweep will be made to cover the first three modes maintaining a constant vibration force. Resonant frequencies of these modes will be recorded. The g levels and phase relationships will be determined at 20-inch increments of the blade length. This procedure will be repeated for the other two modes.

Chordwise Frequency Test

Vibration forces will be induced from the horizontal direction at the same radial station used for the flapwise direction. The flapwise frequency test procedure will be followed for the first- and second-mode determination, except that the blade will be probed along the leading edge.

Torsional Frequency Test

Torsional vibration forces will be induced at the blade tip in line and perpendicular to the trailing edge. The chordwise frequency test procedure will be followed for the first and second torsional modes. An additional three locations will be monitored at each blade station: near the leading edge, on the pitch axis, and near the trailing edge.

Bench Fatigue Test of Spar-to-Box Joint

The purpose of this test is to substantiate the fatigue strength and life of the spar-to-box joint. The test specimen will consist of a root-end section of spar approximately 100 inches long complete with blade boxes. The specimen will be reinforced and fitted at the ends with internal plugs for attachment to a blade fatigue fixture. The specimen will also be internally reinforced at 1/3 and 2/3 of the length; at these locations loading clamps will circumscribe the specimen. The specimen will be strain-gaged to define moments and strains.

The specimen will be statically calibrated to obtain a relationship between strain-gage output and known bending moment. This relationship is used to obtain the dynamic bending moments.

The test specimen will be installed in a test fixture as a pin-pin beam. An axial load will then be applied to the specimen. Bending moments will be induced in the specimen by shear loads applied at the profiled loading clamps enclosing the spar at the internally reinforced locations. The specimen will be force-driven at or close to the aircraft frequency. The entire specimen will be contained in an environmental chamber at -65°F. The specimen will be run for 10,000 cycles at the initial load level. The load level will then be increased after completion of each 10,000 cycles until failure.

Bench Fatigue Test of Blade Root End With Steady Axial Load, Alternating Flap and Chord Bending, and Torque

This test is to substantiate the structural adequacy at the root end of the sectionalized rotor blade when subjected to steady axial load and alternating flap and chord moments, together with alternating torque.

The test specimen will consist of a root-end section cut from the full-length blade used for the static blade tests and nonrotating natural frequency tests. The blade section will be instrumented to measure flapwise and chordwise bending moments and torque. The inboard end of the specimen will be held in the loading fixture by a dummy part simulating the normal aircraft spar retention system. The outboard end of the spar will be reinforced and fitted with an internal plug which attaches to the loading fixture.

The specimen will be installed in a test fixture as a pin-pin beam and excited at a frequency of approximately 0.5 Hertz. The steady axial load will be applied by a springbank arrangement to the inboard end of the blade. The flap and chord moments will be applied by a single shear load to the dummy part inboard of the specimen. The flap-to-chord relationship will be obtained by varying the pitch angle of the specimen.

Except for the steady axial load, all loads will be applied by a servocontrolled hydraulic actuator which will incorporate phase control.

The specimen will initially be statically calibrated with flap, chord, and torque moments to obtain a relationship between known bending moment and strain, This relationship is used later to define dynamic bending moment. The specimen will then be installed in the dynamic test fixture. The specimen will be cycled at a load level selected to give a 10 x 10^6 cycle runout. Subsequently the load levels, except for the steady axial, will be increased after each 2 x 10^6 cycles until failure. All strain and moment levels will be recorded at each load increment.

Bench Fatigue Test of Blade Intermediate Section With Axial Load and Combined Bending

This test is to substantiate the structural adequacy at an intermediate section of the sectionalized rotor blade, subjected to axial load simulating centrifugal force and combined flap and chord bending.

The test specimen will consist of approximately the middle third cut from the full-length blade used for the static and nonrotating natural frequency tests. The specimen will be instrumented to define flapwise and chordwise bending moments and strains in the spar. The blade section will be locally reinforced and fitted with an internal plug at each end for adaptation to the test fixture.

The test specimen will be installed in a test fixture as a pin-pin beam and an axial tension load will be applied in conjunction with flap and chord bending moments. The relationship between flap and chord moments will be obtained by varying the pitch angle of the blade. The specimen will be excited at its first-mode natural resonant frequency by a servocontrolled hydraulic actuator, producing in-phase flapwise and chordwise bending moments. Tuning weights will be added if necessary to reach the required load levels.

The specimen will be initially statically calibrated in pure flapwise and chordwise bending as a simply supported beam to obtain the relationship between strain-gage output and bending moment. The specimen will then be installed in the dynamic test fixture. The first load level will be selected so that the specimen will achieve a 10 x 10^6 cycle runout; subsequently the load level will be increased after each 2 x 10^6 cycles until failure. All strain and moment levels will be recorded at each load increment.

Bench Fatigue Test of Blade Outboard Section With Axial Load and Combined Bending

The purpose of this test is to substantiate the structural adequacy of the outboard section of the sectionalized rotor blade subjected to axial load simulating centrifugal force and combined flap and chord bending.

The test specimen will consist of approximately the outboard third cut from the full-length blade used for the static and nonrotating natural frequency tests. The specimen will be instrumented to define flapwise and chordwise bending moments and will be locally reinforced and fitted with an internal plug at each end for adaptation to the test fixture.

The test specimen will be installed in a test fixture as a pin-pin beam, and the axial tension load will be applied in conjunction with flap and chord bending moments. The relationship between flap and chord moments will be obtained by varying the pitch angle of the blade. The specimen will be excited at its first-mode natural resonant frequency by a servocontrolled hydraulic actuator, producing in-phase flapwise and chordwise bending moments. Tuning weights will be added if necessary to reach the required load levels.

The specimen will be initially statically calibrated in pure flapwise and chordwise bending as a simply supported beam to obtain the relationship between strain-gage output and bending moment. The specimen will then be installed in the dynamic test fixture. The first load level will be selected so that the specimen will achieve a 10×10^6 cycle runout; subsequently the load level will be increased after each 2×10^6 cycles until failure. All strain and moment levels will be recorded at each load increment.

WHIRL TEST

The purpose of this test is to obtain strain data and accomplish preflight safety substantiation of the sectionalized main rotor blade. The test specimens shall consist of two complete blade assemblies adequately instrumented to obtain all pertinent data.

The specimens will be set up in the whirl tower at Boeing-Vertol Facility 2B. An associated rotary-wing head and upper flight controls shall be installed on the tower.

The initial run shall be made with a collective pitch angle input of 2 degrees and the blades shall be slowly accelerated to 200 rpm. Data shall be continuously recorded during acceleration and at stabilized rotor speeds of 100, 150, and 200 rpm. Blade tracking shall commence with 2 degrees of collective angle input and 200 rpm and continue at 210, 220, 230, 240, 250, and 260 rpm. Pitch link and trailing-edge changes shall be made to adjust the flat track within 1/8 inch. A collective track shall be conducted at 230 rotor rpm and at 2-degree collective pitch angle input increments between 2 and 12 degrees. Tracking weights shall be relocated to adjust the collective track within 1/8 inch.

Stress and Motion Survey

Track measurements shall be recorded during all stress and motion survey runs. The following matrix of configurations shall be performed for the stress and motion survey:

Rotor Speed (RPM)	Collective Pitch Angle Input (Deg)	Cyclic Pitch Angle Input (Deg)
270		
285	Various	Various
300	pitch	cyclic
315	angles	pitch
324		angles

Cyclic pitch angle input shall be limited to avoid droopstop pounding, and rotor horsepower shall not exceed 3,750. Indicated thrust and torque shall be recorded for stabilized rotor speeds of 225 to 250 rpm with collective pitch angle inputs of 2 degrees to 11.75 degrees at 1-degree increments with an upper limit of 3,750 horsepower.

Endurance Test

The endurance test shall consist of the test hours accumulated during the stress and motion survey plus the following:

Time (Hr)	Rotor Speed (RPM)	Horsepower	Collective Angle Estimated (Deg)	Cyclic Angle (Deg)
2	270	As	9.2	4
3	300	required	9.8	4
5	324		10.9	4

The above shall be repeated until a total of 49.75 hours of testing has been completed. The final test run will be an overspeed condition of 15 minutes duration (50 hours grand total) at flat pitch at the maximum safe rpm for the hub components.

FLIGHT TEST

The proposed sectionalized main rotor blade is identical to the current production main rotor blade in regard to airfoil section, span, and twist. Repairability of the proposed blade can be adequately demonstrated in ground tests. The combination of damage that the proposed blade could sustain is almost infinite and therefore uneconomical to flight test. Rather, this effort should be left to pilot discretion to reduce rotor rpm and airspeed (and thus the vibration level) for the prevailing conditions at the time of occurrence. It is conceivable but unlikely that the outboard leading-edge cap could be so damaged and the airflow so disrupted as to make the aircraft unflyable.

For these reasons, it is proposed to limit the flight test program to the following objectives:

1. Verification of the rotor blade structural integrity throughout the current flight handbook envelopes (blades intact)

2. Verification of the rotor system compatibility (vibration) throughout the current flight handbook envelopes (blades intact)

3. Flying qualities and performance evaluation with crushed outboard leading-edge caps (both blades)

Rotor Blade Structural Verification

Instrumented rotor blade and rotor shaft data shall be recorded while flying the aircraft at selected combinations of airspeed, rotor rpm, altitude, accelerations, gross weight, and center-of-gravity positions. The selected combinations shall be so chosen that a safe and logical buildup to the flight handbook envelope extremes can be monitored in a remote ground station.

Rotor System Compatibility Verification

Cockpit, cabin, and other pertinent structural vibration data shall be recorded during the rotor blade structural verification tests.

Crushed Outboard Leading Edge Evaluation

For this test, both outboard leading-edge protective caps shall be deformed in such a manner that the protective gap between the spar and cap is zero at a point midway between each attaching screw (scalloped). The instrumented data shall be recorded at airspeeds and rotor speeds selected by the pilot.

Instrumentation

A suitable in-flight recorder and associated circuitry shall be installed in the test aircraft to simultaneously record the following:

1. Rotor blade loads (20 locations plus 100 percent spares)
2. Rotor shaft lift
3. Rotor shaft bending
4. Rotor shaft torque
5. Pitch link load
6. Cockpit vibration (vertical, lateral, and longitudinal)
7. Cabin vibration (vertical, lateral, and longitudinal)
8. Main transmission vibration (vertical, lateral, and longitudional)
9. Tail boom vibration (vertical, lateral, and torsional)
10. Rotor speed
11. Rotor 1/rev
12. Airspeed
13. Altitude
14. Outside air temperature
15. Cockpit control positions (4)
16. Vertical acceleration at the center of gravity
17. Pitch, roll, and yaw attitudes
18. Pitch, roll, and yaw rates
19. Engine torque
20. Engine N_1 speed
21. Engine exhaust gas temperature or turbine inlet temperature
22. Event marker or record counter

Critical data for monitoring flight safety shall be telemetered to a remote ground station.

NOTE

In the contractor's opinion the whirl test and flight test could be performed more economically at the facilities of Bell or the Army. The whirl tower at Boeing's Vertol Division would have to be modified to take the UH-1H rotor. A hub adapter and a modified control system would have to be designed, manufactured, and installed on the tower. Extra cost could be eliminated by whirling the blades at Bell's facilities.

Similarly, flight testing could be done more economically either by Bell or by the Army. The training of pilots and mechanics would be required if flight tests were to be conducted by Boeing-Vertol.

ESTIMATED DIRECT LABOR MANHOUR REQUIREMENTS

TABLE XII. DEVELOPMENT COST ESTIMATE - SUMMARY CHART

Program Element	Engineering Manhours	Manufacturing Manhours	Materials ($)
Design and Fabrication	8,700	45,000	61,000
Analysis	600	-	-
Element Test	1,400	2,000	10,000
Bench Test	4,000	5,500	12,000
Whirl Test	2,500	3,100	1,000
Flight Test	4,300	7,500	32,000
Reports	1,200	-	-
Totals	22,700	63,100	$116,000*

*Unburdened direct material dollars

ESTIMATED SCHEDULE

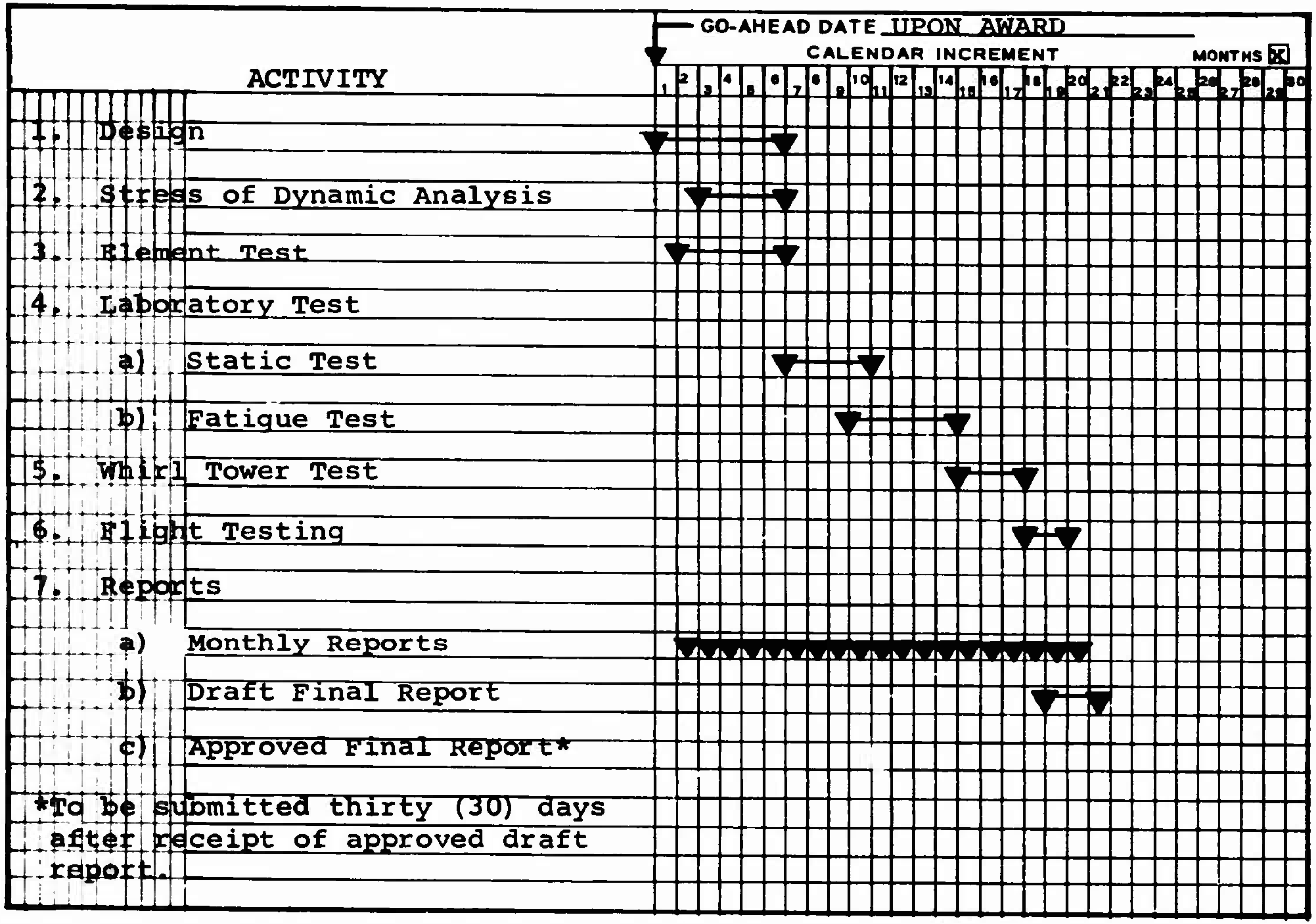


Figure 47. Performance Schedule of Future Hardware Evaluation.