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HIGHLY SURVIVABLE TRUSS TYPE TAIL BOOM,(U)
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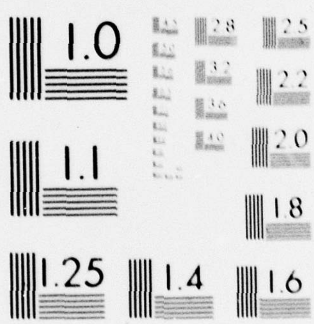
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6 HIGHLY SURVIVABLE TRUSS TYPE TAIL BOOM,

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INTRODUCTION. Successful completion of Army helicopter missions in future battle scenarios may well depend upon survival of the structure after battle damage. Survivability of a helicopter will depend significantly upon the structure's ability to retain structural integrity. The principle purpose of this study is to develop a structural concept which assures a high degree of confidence in the integrity of a structure that has received combat damage. This study has been pursued because the Army needs to meet and provide a solution to the ever escalating high explosive anti-aircraft threat to the helicopter tail boom.

The highly lethal 23mm high explosive projectile represents an existing widely deployed threat to Army helicopters. The more lethal 30mm high explosive projectile appears on the horizon as the potential future threat. Because of this potentially severe 30mm threat and the possible inadequacy of present semimonocoque designs to survive hits by the 30mm, the present study was initiated to develop a structural challenge to the 30mm and to improve upon the present designs.

The tail boom of a helicopter (for example, the present AH-1 and UH-1 models) presents a significant amount of vulnerable area, and due to the flight loads of the tail rotor and elevators, the tail boom is constantly in some stressed condition. The semimonocoque tail boom construction configuration consists of skins, longerons, stringers, and bulkheads. Four longerons provide the main bending support for the tail boom. Shear loads are carried by the skin structure which is locally supported against buckling by the stringers. Presently the semimonocoque structure is configured to the minimum weight design.

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Ballistics tests using the 23mm high explosive against the minimum weight semimonocoque tail boom design have demonstrated its lack of damage tolerance.(1) Structural modifications have been shown to increase the damage tolerance of the structure but the amount of damage is predictably a function of confined volume and detonation distance to the surface.(1) Clearly the larger 30mm projectile reduces the survivability of the entire semimonocoque tail boom structure.

The solution for a structural challenge in this study took the form of a search for a highly redundant tail boom structure. A highly redundant structure is a structure that starts with a compact unit structure. The compact unit structure is interconnected within itself by comparatively small, relative to the entire structure, but stiff structural elements. The entire structure is then built up by a replication of the unit structure, scaling as desired or necessitated. The main reason for a high degree of redundancy is to build-in damage tolerance by attempting to keep damage strictly localized.

A possible engineering solution that can easily be made highly redundant is the truss type structure. Use of modern technology and standard elements can make a truss both practical and economical. Because of its potential to fulfill such characteristics, the truss type structure was selected for this study in place of the semimonocoque structure. This study not only utilizes the truss concept but also introduces the concept of complete imbedded substructures. Complete imbedded substructures are easily generated within a truss structure that has a base figure equivalent to a quadralateral by including the interior diagonals in a simple open truss structure. The intent is to develop a truss type tail boom with complete substructures that is highly redundant so that it can absorb massive damage and yet still hold the aerodynamic loads of flight. The truss tail boom can reduce vulnerability while lowering the weight of the tail boom. The observable surface area drops significantly reducing visibility and radar echo. A bonus would be the possibility of mounting a recoilless rifle on the helicopter because the openness of the truss allows the passage of back blast.

The development was performed throughout by computer modeling. The aerodynamics loads can be simulated and a damage criterion established very easily by this technique. A damage criterion should reflect a maximum amount of damage that can be sustained by the structure. The design objective is to retain structural integrity after imposition of the damage criterion.

Damage to a truss structure would not be in terms of confined volume or surface distance as it is in the semimonocoque structure, but damage would be in terms of loss of a member(s) or a loss of a joint. Not counting a completely destructive blast, the most catastrophic single event that could occur to a truss structure would be the destruction of a joint. The loss of a joint in a truss structure can be considered as massive damage because the loss of many members assembled at the joint is associated with loss of the joint. The demand that the truss sustain loss of a single joint and still retain structural integrity (not have other members buckle or fail) under flight loads is considered maximum survivability for the purpose of this study. Thus, loss of a joint is the damage criterion employed in this study.

Static and dynamic analysis of two truss design concepts were performed by the NASTRAN (NASA STRuctural ANalysis) program. One of these truss concepts is a simple open truss design. The other model incorporates the concept of complete substructures. The semimonocoque tail boom of AH-1 helicopter series is used as the basis for a replacement truss tail boom model. The AH-1 series helicopter presents a logical choice to develop a truss structure tail boom to replace a semimonocoque structure. This helicopter has been in the Army's arsenal for a while and will continue in service for a number of years.

PROCEDURES. The longerons are the longitudinal elements which constitute the basic configuration to be employed in the truss structure model development. The basic overall dimensions come from the AH-1G helicopter reported in reference (2) (see Figure 1). Longeron pattern at the larger (or base) end has been selected to conform to the bolt pattern of the AH-1G model at the tail boom - main fuselage manufacturing break line. The aerodynamic loading conditions were obtained from Bell Helicopter Company.(3) Common design parameters and formulas are listed in Table 1. Consideration of cost and logistics leads the ideal design concept to have all structural truss members with the same cross sectional dimensions. There is less cost involved buying large quantities of structural elements all the same size than small quantities of various sizes. The standard tube(4) structural element of 3.81cm (1 1/2 in) outside diameter and .159cm (1/16 in) thickness was chosen for this study because of its higher inertia over rods of the same cross sectional area.

Initial model goal was a high degree redundancy. The goal was achieved by orienting outside diagonals at 45° angles, which generated a large number of joints (44) within the dimensional bounds of Figure 1. Though truly highly redundant and damage tolerant, the geometric configuration is not a low weight design. To obtain a geometric configuration conducive to a low weight design without doing a geometry optimization analysis, this study utilizes only the joint locations described in reference (7). Thus, both models of this

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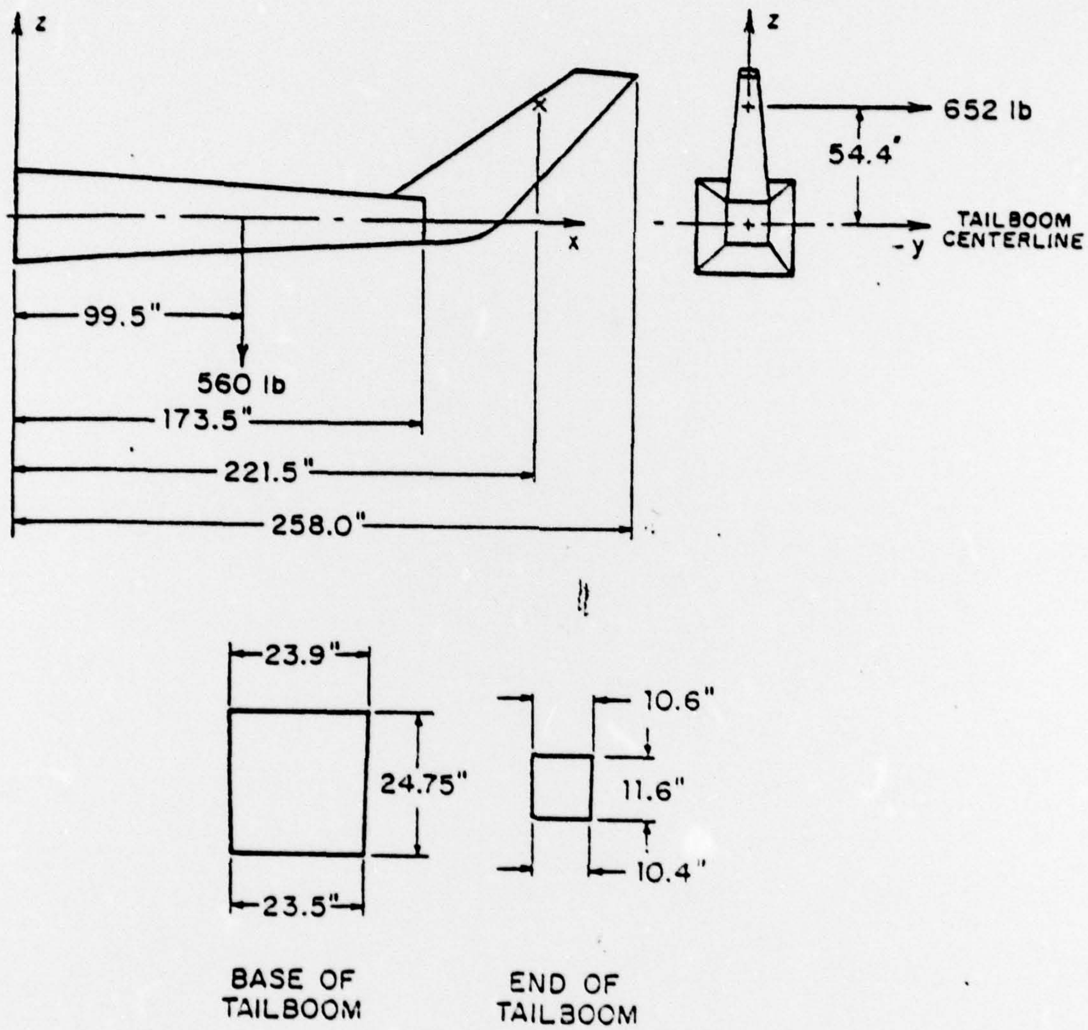

Figure 1. Geometry of Helicopter Tail Boom.

TABLE 1.
Common Design Parameters and Formulas

Material: Aluminum Alloy

Modulus of Elasticity: $E = 7. \times 10^{10}\ n/m^2 (10.5 \times 10^6\ psi)$ (4)

Density ρ: $\rho = 2.7 \times 10^3\ kg/m^3 (0.1\ lbs/in^3)$ (4)

Margin of Safety:
of Individual Member $M.S. = \dfrac{\text{stress limit}}{\text{applied stress}} - 1.$ (5)

Stress Limits per member

Compressive $CSL = .8 * \delta_{cr}$

Tensile $TSL = \delta_{cr}$

Euler Column Buckling (6)

$$\delta_{cr} = \frac{Pcr}{CSA}$$

Cross Sectional Area of Tube: $CSA = .\pi(r_o^2 - r_i^2)$

Compressive Critical Load with Hinged Ends (6)

$$Pcr = \frac{\pi^2 EI}{l^2}$$ where l = length of member

study have 28 joints and 72 degrees of freedom. Model 1 is an open truss framework containing 114 members (see Figure 2). Model 2 is a substructured truss framework by the inclusion of the interior diagonals generating a total of 138 members (see Figure 3). The chosen standard structural tube element makes Model 1 weigh approximately 40.8 kg (90 lbs), and Model 2 weigh approximately 52.2 kg (115 lbs).

Static and dynamic analyses were performed on both models by NASTRAN.(8) NASTRAN is a large, comprehensive, general purpose, finite element, displacement method computer program. Design and analysis of all forms of airframes have been carried on by NASA, aerospace industries and other government agencies for a number of years by use of NASTRAN.

The loading that corresponds to the maximum, 130 kt. level flight condition(3) was applied to each complete model and its subsequent damage cases. The application of the 130 knot level flight load was

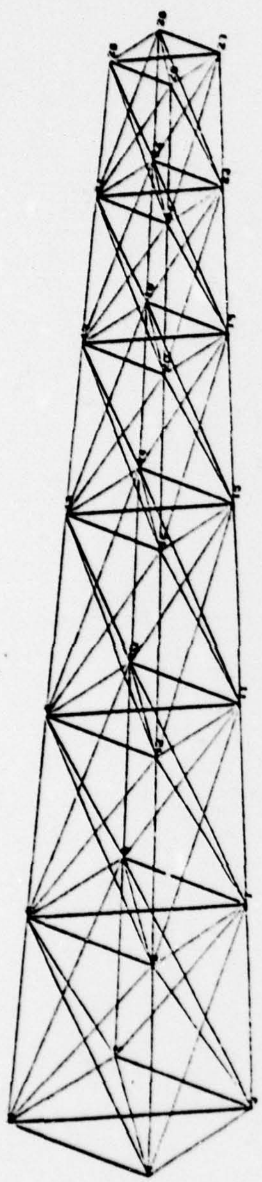

Figure 2. Computer Drawing of Model 1.

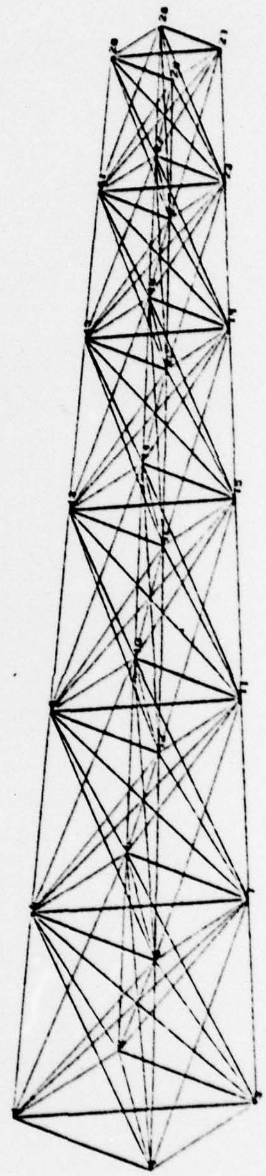

Figure 3. Computer Drawing of Model 2.

simulated using NASTRAN rigid format 4, Static Analysis with Differential Stiffness outputting displacements, stresses and margins of safety. More accurate design operating stresses are calculated for analysis of buckling failure to individual members by this method(9) over NASTRAN rigid format 1, Static Analysis.

Buckling failure determined by margin of safety for each individual element is calculated in NASTRAN according to the relations given in Table 1. Buckling due to compressive stress occurs before failure of an element due to tension. An additional 20% safety factor is included for compressive stress limits. A margin of safety less than zero indicates failure. A margin of safety between zero and one indicates structural integrity and is acceptable. Margin of safety greater than one is preferred for the purposes of this study.

The complete models were analyzed first with the 130 knot flight loads applied. Then the imposition of the damage criterion was simulated by removing a joint and all elements connecting that joint. A vertical station in front, middle, and rear of the models were chosen to have their joints deleted one at a time and then the damaged structure was reanalyzed with the same applied flight loads. A total of twelve damaged cases were simulated.

Realistically, portions of members that enter a joint may remain affixed to the truss structure after loss of a joint. The effects of these members (or portions thereof) remaining are considered minor, and therefore are neglected in this study.

RESULTS. Maximum deflection constraint due to tail rotor driveshaft couplings (10) is 8.13cm (3.2 in). Table 2 shows maximum displacements of the truss models with and without damage imposed. These displacements lie comfortably within this maximum deflection constraint. The complete semimonocoque tail boom structure weighs approximately 90.72 kg (200 lbs)(3) and its deflections due to the 130 knot level flight load are 1.37cm (.539in) in y direction and .37cm (.146 in) in the z direction.(10) The complete truss models which weigh about half the semimonocoque tail boom weight, show as indicated by Table 2, a stiffness 12% greater in the y direction and 46% less in the z direction. Considering the weight difference the truss models stiffness is reasonably competitive. Table 2 shows a maximum increase in the y direction displacement of .82cm more than the undamaged case occurring in the case where joint 5 is deleted. It shows a maximum increase in the z direction displacement of .803cm more than the undamaged case occurring in the case where joint 7 is deleted.

TABLE 2.
Maximum Displacement at End of Boom Due to 100% Flight Load.

	MODEL 1		MODEL 2	
Damage	y	z	y	z
none	1.09cm(.430 in)	.797cm(.314 in)	1.10cm(.433 in)	.784cm(.309 in)
-5	1.91cm(.754)	1.55cm(.611)	1.89cm(.745)	1.53cm(.603)
-6	1.10cm(.435)	.955cm(.376)	1.10cm(.435)	.935cm(.368)
-7	1.83cm(.721)	1.60cm(.629)	1.84cm(.725)	1.53cm(.605)
-8	1.17cm(.463)	1.01cm(.399)	1.13cm(.448)	.950cm(.374)
-13	1.55cm(.610)	1.04cm(.411)	1.50cm(.591)	1.04cm(.411)
-14	1.32cm(.522)	.630cm(.248)	1.33cm(.525)	.635cm(.250)
-15	1.34cm(.529)	1.22cm(.482)	1.37cm(.541)	1.14cm(.449)
-16	1.53cm(.603)	.81cm(.319)	1.46cm(.576)	.726cm(.286)
-21	1.43cm(.565)	.889cm(.350)	1.36cm(.538)	.899cm(.354)
-22	1.15cm(.454)	.726cm(.286)	1.19cm(.469)	.741cm(.292)
-23	1.17cm(.462)	1.10cm(.436)	1.21cm(.479)	1.01cm(.399)
-24	1.39cm(.550)	.924cm(.364)	1.33cm(.524)	.843cm(.332)

Members in tension have been found to have margins of safety greater than 1.0. Compressive margins of safety under 1.0 do occur due to imposition of the damage criterion. (Table 3 is a key for Tables 4, 5 and 6). Since changes in margins of safety only occur locally, only the damage criterion in the neighborhood of the joint in question is presented. Tables 4, 5, and 6 show the compressive margins of safety and change in load path due to imposition of the damage criterion.

The compressive margins of safety (M.S.) shown in Tables 4, 5, and 6 indicate load path redistributions due to the damage cases. The comparison made between model 1 and model 2 shows the interior diagonals of model 2 to be working by taking on tensile and compressive loads. Though no members of model 1 or model 2 failed, Table 7 extracts four cases from Table 4 and 5 where M.S. is under 1.0 for model 1 and two cases for model 2. Table 7 also shows that substructured model 2 consistently has M.S. greater where needed than the open truss model 1. Also, to be noted in Table 7 is a 75% loading condition for two cases out of the four where the M.S. is less than 1.0 for model 1 and comparative M.S. over 1.0 for the substructured model 2.

Table 8 shows the maximum and minimum presented areas and their appropriate orientations. The semimonocoque structure presents a continuous surface whereas the truss models present non-continuous surface areas. For the maximum model 1 has a 47% reduction and model 2 has a 33% reduction in presented area compared to semimonocoque. Comparison of the minimum presented areas show: model 1 has a 80% reduction, and model 2 has a 75% reduction. These reductions show a clear reduction in visibility of the truss tail boom relative to the semimonocoque type tail boom.

TABLE 3 Key for Tables 4, 5, and 6

I.D.	= interior diagonal; O.D. = outside diagonal
T.H.	= transverse horizontal; T.V. = transverse vertical
T.D.	= transverse diagonal; Long. = longeron
J-J	= joint-to-joint connection
D	= deleted member; T = member in tension
-	= Nonexistant member; Blank space = compressive

Margin of Safety greater than 10.0

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TABLE 4. Compressive Margins of Safety Under 10.0 Due to 130 knot Flight Load on Forward Vertical Sta with 100% Loading

DAMAGE			NONE		Joint 5		Joint 6		Joint 7		Joint 8	
MODEL			1	2	1	2	1	2	1	2	1	2
MEMBER	J-J	No#										
Long.	1-5	7	T	T	D	D	T	T	T	T	T	T
"	2-6	8			T	T	D	D	2.0	2.3		
"	3-7	9	3.6	3.6	1.4	1.3	4.1	4.1	D	D	1.9	2.2
"	4-8	10	T	T	T	T	T	T			D	D
O.D.	1-6	11		8.0	8.4	10.	D	D	2.8	2.2		7.1
"	2-5	12	T	T	D	D	T	T	T	T	T	T
"	1-8	13	T	T	T	T	T	T	T	T	D	D
"	4-5	14			D	D	8.7	7.6	T	T	1.6	3.0
"	4-7	15	T	T	T	T	T	T	D	D	T	T
"	3-8	16	2.0	2.2	2.8	2.6	2.3	2.3	.36	.71	D	D
"	2-7	17	2.0	2.0	1.5	1.3	1.2	1.4	D	D	1.5	1.2
"	3-6	18	T	T	T	T	D	D	T	T	T	T
I.D.	1-7	19	-	T	-	T	-		-	D	-	T
"	2-8	20	-		-	T	-		-	3.2	-	D
"	3-5	21	-		-	D	-	T	-		-	3.7
"	4-6	22	-	T	-		-	D	-	T	-	T
T.V.	5-6	23			D	D	D	D				
T.H.	5-8	24			D	D					D	D
T.V.	7-8	25	T	T	T	T	T	T	D	D	D	D
T.H.	6-7	26	T	T	T	T	D	D	D	D	T	T
T.D.	5-7	27	T		D	D	T	T	D	D		
"	6-8	28			4.0	3.5	D	D	T	T	D	D
Long.	5-9	29	T	T	D	D	T	T	T	T	T	T
"	6-10	30	T	T	T	T	D	D				T
"	7-11	31	4.4	4.4	1.8	1.8	1.9	2.2	D	D		8.5
"	8-12	32			T	T	T		2.5	3.1	D	D
O.D.	5-10	33	8.6	7.0	D	D	1.6	2.4	T		6.9	4.9
"	6-9	34	T	T	T	T	D	D	T	T		T
"	5-12	35	T	T	D	D	T	T	T	T	T	T
"	8-9	36	6.0	5.7	3.7	5.6		5.7	2.2	1.9	D	D
"	8-11	37	T	T	T	T	T	T	T	T	D	D
"	7-12	38	1.7	1.9	1.3	1.1	1.2	1.1	D	D	.81	1.2
"	6-11	39	2.3	2.3	3.1	2.6	D	D	.44	.79	2.6	2.1
"	7-10	40	T	T	T	T	T	T	D	D	T	T
I.D.	5-11	41	-	T	-	D	-	5.1	-	T	-	T
"	6-12	42	-		-	T	-	D	-	3.0	-	
"	7-9	43	-		-		-	T	-	D	-	7.5
"	8-10	44	-	T	-		-	T	-	T	-	D

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TABLE 5. Compressive Margins of Safety Under 10.0 Due to 130 knot Flight Load on Middle Vertical Sta with 100% Loading

DAMAGE			None		Joint 13		Joint 14		Joint 15		Joint 16	
MODEL			1	2	1	2	1	2	1	2	1	2
MEMBER	J-J	No.#										
Long.	9-13	51	T	T	D	D	T	T	T	T	T	T
"	10-14	52	T	T	T	T	D	D	5.1	7.5	T	T
"	11-15	53	6.2	6.2	3.0	3.0	T	T	D	D	1.5	1.9
"	12-16	54			7.6	8.5	5.6	6.1			D	D
O.D.	9-14	55	7.0	5.6	2.5	3.7	D	D	2.9	2.2	T	8.4
"	10-13	56	T	T	D	D	T	T	T	T	T	T
"	9-16	57	T	T	T	T	T	T	T	T	D	D
"	12-13	58	3.5	3.4	D	D	3.8	3.0	10.	4.7	.62	1.1
"	12-15	59	T	T	T	T	T	T	D	D	T	T
"	11-16	60	1.3	1.5	1.3	1.2	1.3	1.2	.24	.56	D	D
"	10-15	61	2.3	2.3	2.2	1.7	1.2	1.7	D	D	1.2	1.0
"	11-14	62	T	T	T	T	D	D	T	T	T	T
I.D.	9-15	63	-	T	-	T	-		-	D	-	T
"	10-16	64	-		-	T	-		-	3.2	-	D
"	11-13	65	-		-	D	-	T	-		-	2.9
"	12-14	66	-	T	-		-	D	-	T	-	T
T.V.	13-14	67			D	D	D	D				
T.H.	13-16	68			D	D	T	T			D	D
T.V.	15-16	69	T	T	T	T	T	T	D	D	D	D
T.H.	14-15	70	T	T	T	T	D	D	D	D		
T.D.	13-15	71			D	D			D	D	T	T
T.D.	14-16	72					D	D	T	T	D	D
Long.	13-17	73	T	T	D	D	T	T	T	T		
"	14-18	74	T	T	T	T	D	D	T	T	T	T
"	15-19	75	9.8	9.9	4.8	4.9	4.7	5.7	D	D		
"	16-20	76			T	T	5.9	5.8	2.6	3.1	D	D
O.D.	13-18	77	5.4	5.4	D	D	1.7	2.9		7.2	3.2	2.8
"	14-17	78	T	T	T	T	D	D	T	T	T	T
"	13-20	79	T	T	D	D	T	T	T	T	T	T
"	16-17	80	4.0	3.9	2.1	2.9	4.8	3.0	2.2	1.9	D	D
"	16-19	81	T	T	T	T	T	T	T	T	D	D
"	15-20	82	2.3	2.3	2.3	1.8	2.1	1.7	D	D	.87	1.2
"	14-19	83	3.3	3.4	3.3	2.8	D	D	.82	1.3	5.5	4.1
"	15-18	84	T	T	T	T	T	T	D	D	T	T
I.D.	13-19	85	-		-	D	-	5.9	-		-	T
"	14-20	86	-		-	T	-	D	-	4.2	-	
"	15-17	87	-	T	-	T	-	T	-	D	-	7.3
"	16-18	88	-	T	-		-	T	-	T	-	D

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TABLE 6. Compressive Margins of Safety Under 10.0 Due to 130 knot Flight Load on End Vertical Sta with 100% Loading

DAMAGE MODEL MEMBER	J-J	No#	None 1	None 2	Joint 21 1	Joint 21 2	Joint 22 1	Joint 22 2	Joint 23 1	Joint 23 2	Joint 24 1	Joint 24 2
Long.	17-21	95	T	T	D	D	T	T	T	T	T	T
"	18-22	96	T	T	T	T	D	D			T	T
"	19-23	97			5.4	5.6	T	T	D	D	3.2	3.7
"	20-24	98			7.8	9.1	6.6	6.8			D	D
O.D.	17-22	99	6.5	6.5	2.6	4.1	D	D	3.6	3.2		9.1
"	18-21	100	T	T	D	D	T	T	T	T	T	T
"	17-24	101	T	T	T	T	T	T	T	T	D	D
"	20-21	102	5.1	4.9	D	D	5.0	4.1	6.5	6.5	1.4	2.0
"	20-23	103	T	T	T	T	T	T	D	D	T	T
"	19-24	104	2.9	2.9	2.9	2.4	3.0	2.4	1.1	1.5	D	D
"	18-23	105	4.2	4.3	4.1	3.1	2.3	3.3	D	D	2.5	2.2
"	19-22	106	T	T	T	T	D	D	T	T	T	T
I.D.	17-23	107	-		-		-	10.	-	D	-	T
"	18-24	108	-		-	T	-		-	6.7	-	D
"	19-21	109	-	T	-	D	-	T	-	T	-	6.1
"	20-22	110	-	T	-	9.6	-	D	-	T	-	T
T.V.	21-22	111			D	D	D	D				
T.H.	21-24	112			D	D	T	T			D	D
T.V.	23-24	113	T	T	T	T	T	T	D	D	D	D
T.H.	22-23	114			T	T	D	D	D	D		
T.D.	21-23	115		T	D	D			D	D	T	T
T.D.	22-24	116	T				D	D	T	T	D	D
Long.	21-25	117	T	T	D	D	T	T	T	T		
"	22-26	118	T	T	T	T	D	D	T	T	T	T
"	23-27	119			6.7	7.1	5.6	7.4	D	D		
"	24-28	120			T	T	7.8	7.3	3.4	3.9	D	D
O.D.	21-26	121	7.3	7.2	D	D	2.4	4.0			4.1	3.7
"	22-25	122	T	T	T	T	D	D	T	T	T	T
"	21-28	123	T	T	D	D	T	T	T	T	T	T
"	24-25	124	5.0	4.8	2.9	4.0	6.0	3.7	2.9	2.4	D	D
"	24-27	125	T	T	T	T	T	T	T	T	D	D
"	23-28	126	3.1	3.1	2.9	2.3	2.8	2.3	D	D	1.2	1.6
"	22-27	127	4.2	4.4	4.3	3.7	D	D	1.2	1.9	7.4	5.6
"	23-26	128	T	T	T	T	T	T	D	D	T	T
I.D.	21-27	129	-		-	D	-	6.2	-		-	T
"	22-28	130	-	T	-	T	-	D	-	6.3	-	
"	23-25	131	-		-	T	-	T	-	D	-	8.0
"	24-26	132	-	T	-		-	T	-	T	-	D

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TABLE 7. Cases of Models 1 and 2 Where M.S. Less Than 1.0

Case Where Damage is - Joint 7

Loading	Element #	J-J	Model 1 M.S.	Model 2 M.S.
100%	16	3-8	.36	.71
	39	6-11	.44	.79
75%	16	3-8	.82	1.3
	39	6-11	.94	1.4

Case Where Damage is - Joint 8

Loading	Element #	J-J	Model 1 M.S.	Model 2 M.S.
100%	38	7-12	.81	1.2

Case Where Damage is - Joint 15

Loading	Element #	J-J	Model 1 M.S.	Model 2 M.S.
100%	60	11-16	.24	.56
	83	14-19	.82	1.3
75%	60	11-16	.66	1.1

Case Where Damage is - Joint 16

Loading	Element #	J-J	Model 1 M.S.	Model 2 M.S.
100%	58	12-13	.62	1.1
	82	15-20	.87	1.2

TABLE 8. Observable Presented Area

	Maximum Orientation	Minimum Orientation
AH-1G Semimonocoque	58,655cm^2(4546 in^2)Side	39,233cm^2(3506 in^2)Bottom
Truss Model 1	31,354cm^2(2430 in^2)Oblique	7,838cm^2(608 in^2)Side
Truss Model 2	39,019cm^2(3024 in^2)Oblique	9,754cm^2(756 in^2)Side

CONCLUSIONS. The truss type tail boom models of this study provide a reduction in weight of approximately 50% over the present semimonocoque tail boom structure of the AH-1G. The truss models are reasonably stiff structures compared to the semimonocoque structure.

Analyses of the highly redundant truss models under the aerodynamic loads of flight and with imposition of a massive damage criterion show:

- Substantial retention of stiffness
- Change of load path that is localized
- No failure of elements due to tension or compression
- Retention of structural integrity

The substructured truss model has more supporting structural elements to redistribute the load and consistently has margins of safety higher than the non-substructured truss model. The substructuring concept has vulnerability reduction built-in. The substructure concept assures a higher degree of confidence in the truss concept to retain structural integrity after imposition of the loss of a joint. The substructured truss model has at least a 33% reduction in presented area compared to the semimonocoque structure. The highly redundant substructured truss type tail boom is a highly survivable structure.

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