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LEVEL II

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COMBAT MAINTENANCE CONCEPTS AND REPAIR TECHNIQUES FOR HELICOPTER AIRFRAME STRUCTURES

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APPLIED TECHNOLOGY LABORATORY
U. S. ARMY RESEARCH AND TECHNOLOGY LABORATORIES (AVRADCOM)
Fort Eustis, Va. 23604

APPLIED TECHNOLOGY LABORATORY POSITION STATEMENT

This investigation is part of a program being conducted by the Applied Technology Laboratory to reduce maintenance downtime of Army aircraft during combat operations.

The results of this investigation indicate that the majority of damage to the UH-60A airframe due to armor piercing incendiary (API) and high explosive incendiary (HEI) projectiles can be deferred. However, the reader is advised that according to the contract statement of work, the analysis was to consider only damage to the airframe because a total damage assessment was beyond the scope of this effort. Development of the combat damage assessment technique was more important than the development of the deferrability assessment. This damage assessment technique is believed to be equally applicable to both fixed- and rotary-wing aircraft.

This effort, and a parallel effort with Kaman Aerospace Corporation (USAAVRADCOM TR-80-D-40), is the initial step toward development of inspection and repair concepts for combat damage to helicopter structure. The results of both efforts will form the basis for follow-on work, which will be the development of field-usable inspection criteria and repair techniques.

Mr. John Ariano, Aeronautical Systems Division, served as technical monitor for this contract.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Modeling techniques were used to simulate airframe combat damage. Structural analyses were conducted to assess the deferrability and field repairability of the simulated damage cases. A methodology was developed to assess airframe combat damage in the field. Concepts for interim repair of airframe combat damage were investigated.

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SUMMARY

The objectives of this program were to assess the potential for deferring repair of combat damage to the Black Hawk helicopter airframe and to develop concepts for the assessment and repair of airframe combat damage.

A computer model was developed to generate random simulated ballistic strikes on the Black Hawk helicopter airframe. Random shotlines were generated with the model, and cases involving damage to the six primary sections of the airframe were selected for analysis. The FASTGEN computer model was used to trace the path of the simulated shotlines through a geometric description of the Black Hawk helicopter. Aircraft components and structure intersected by each shotline were identified, and the exact points and angles of impact were calculated.

Three computer models based on the THOR equations were obtained from the Naval Weapons Center at China Lake, California. The models were used to calculate the depth of penetration of various projectiles through the components and structure identified by the FASTGEN model. Published data was used to estimate the size of API-type damage to airframe structural members, and detailed damage descriptions were prepared. Computer graphics were used to plot fragment cones for simulated HEI damage cases. The plotted cones were overlaid on views of the structure in the affected areas, and data on fragment density, fragment energy, and explosive blast effects were used to estimate HEI damage. Detailed HEI damage descriptions were prepared.

The simulated API and HEI damage cases were structurally analyzed. Loads criteria, stress reports, and fail-safe testing on the Black Hawk helicopter were used to support the analysis. NASTRAN was used for selected cases. Based on the structural analysis, each damage case was classified with respect to the potential for deferring repair and/or effecting a quick-fix interim repair. Three categories of damage deferrability were considered, and the degradation in attributes associated with operating the aircraft with unrepaired damage was assessed.

Combat damage assessment concepts were evaluated with the objective of developing a technique that would allow Army personnel to assess combat damage in the field. The concept selected is based on a system of failure criticality points and a simplified damage scoring system.

Interim repair concepts were developed for combat damage to four areas of the Black Hawk helicopter airframe. The effectiveness of each concept was evaluated. Recommendations were developed for future efforts in the area of Army helicopter combat maintenance.

PREFACE

This program was performed by the Sikorsky Aircraft Division of United Technologies Corporation under Contract DAAK51-79-C-0049 for the Applied Technology Laboratory (ATL), U. S. Army Research and Technology Laboratories (AVRADCOM), Fort Eustis, Virginia. The program was conducted under the technical direction of Mr. John Ariano of the Reliability, Maintainability, and Mission Technology Technical Area of ATL.

The authors wish to acknowledge important contributions made to this program by the following Sikorsky Aircraft personnel. Mr. Kenneth Kohler of Structures Engineering assisted with the structural analysis of simulated airframe combat damage. Mrs. Louise Cole of R&M Engineering participated in the modeling of ballistic damage cases and assisted with preparation of the final report. Mr. Donald Bartz, Mr. William Bausch, and Mr. Joseph Fukelman of Survivability/Vulnerability Engineering provided guidance on ballistic damage modeling and analysis.

Appreciation is also gratefully extended to Messrs. Robert Grove and Donald Morrow of the Naval Weapons Center, China Lake, California and to Mr. John Thompson of the Falcon Research and Development Co., Englewood, Colorado for valuable contributions to the technical analysis.

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INTRODUCTION

The probability of sustaining damage in combat, its effects on the aircraft, and the problems it presents with respect to repair and return service will vary with the type of aircraft, its mission, and the threat encountered. With newer aircraft such as the UH-60A Black Hawk helicopter, whose designs are heavily influenced by survivability requirements, critical combat damage will occur less frequently and with less severe effects than was experienced with aircraft of the past generation. Although the modern aircraft is much more survivable in combat, it has been observed that this improved survivability adds greatly to the problems of repair in the field. Many more aircraft will be returning from combat, often having suffered heavy damage.

Since airframe structure occupies a very large part of the aircraft, it is highly exposed to combat damage. A ballistic projectile can strike relatively few components of the aircraft without also striking the airframe. When ballistically tolerant and/or redundant components are struck, the modern aircraft will return to base with that damage and frequently with accompanying airframe damage. Airframe damage can be expected to be both the most frequent and some of the most disabling damage the helicopter will suffer.

This report examines the problems associated with the assessment and repair of airframe damage in combat. It is based on a study of the UH-60A Black Hawk helicopter, the first of the Army's new technology aircraft to enter service.

STUDY CANDIDATE

The UH-60A Black Hawk helicopter (Figure 1) is an excellent candidate for the study of combat maintenance concepts for airframe structures. The first of the Army's new technology aircraft to enter service, the Black Hawk is designed to be highly survivable in combat.

Figure 1. UH-60A Black Hawk Helicopter

One of the ways in which modern aircraft such as the Black Hawk are made survivable to combat damage is to employ a large measure of redundancy in critical systems. Hydraulics and flight controls are systems that commonly employ redundant, frequently multiply redundant, components. Airframe structures are also highly redundant. Aside from the redundancy introduced for the purposes of ballistic survivability and crashworthiness, the aircraft is inherently redundant in many areas because it has twin engines, dual flight controls, dual instruments, etc.

When an aircraft lacking redundancy in a flight-essential system suffers debilitating damage to the system, it must be repaired to be flown again, even for the short time that may be needed to return to a friendly site. With redundancy, the aircraft not only returns from the mission safely but might be flown many times again with the damage unrepaired, if the situation warrants that risk.

Because of its survivability characteristics, the Black Hawk will be much more repairable in combat than were earlier-generation aircraft. Ballistic strikes that would cause the loss of less survivable aircraft, or remove them from service for prolonged periods of depot repair, will often be repairable in the field. The ballistic tolerance and structural redundancy incorporated in the airframe greatly increases the opportunity for either deferring repair of combat damage or making quick-fix battlefield repairs.

The Black Hawk is a twin-engine helicopter designed to carry 11 combat-equipped troops and a crew of 3. The airframe is an aluminum semi-monocoque structure 51 ft 3 in. long, 7 ft 9 in. wide, and 5 ft 9 in. high. The six principal sections of the airframe are the cockpit, cabin, rear fuselage, tailcone, tail rotor pylon, and stabilator. The primary structure is comprised of aluminum skins with rolled or extruded aluminum stringers. The fuselage frames are built-up structures with extruded aluminum caps and aluminum sheet webs. In areas where loads are high, the fuselage frames are machined aluminum forgings. In the area of the engines and auxiliary power unit, the fuselage skin is made of annealed titanium to provide a firewall. Sections of primary airframe structure are shown in Figures 2 through 6.

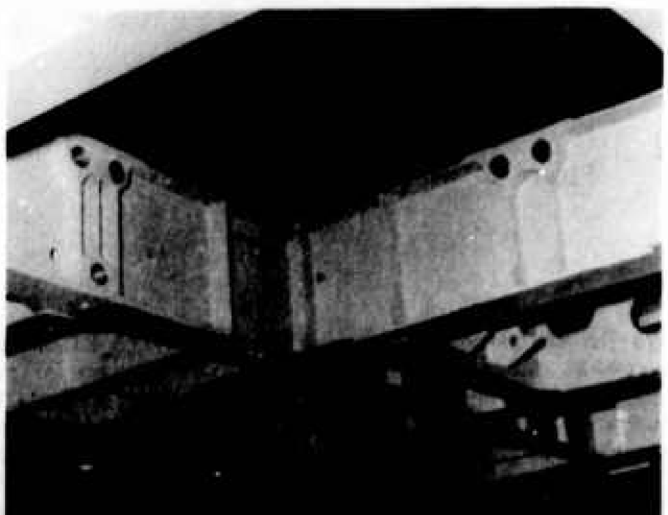

Figure 2. Transmission Support Structure

Figure 3. Rear Fuselage Interior Roof Structure

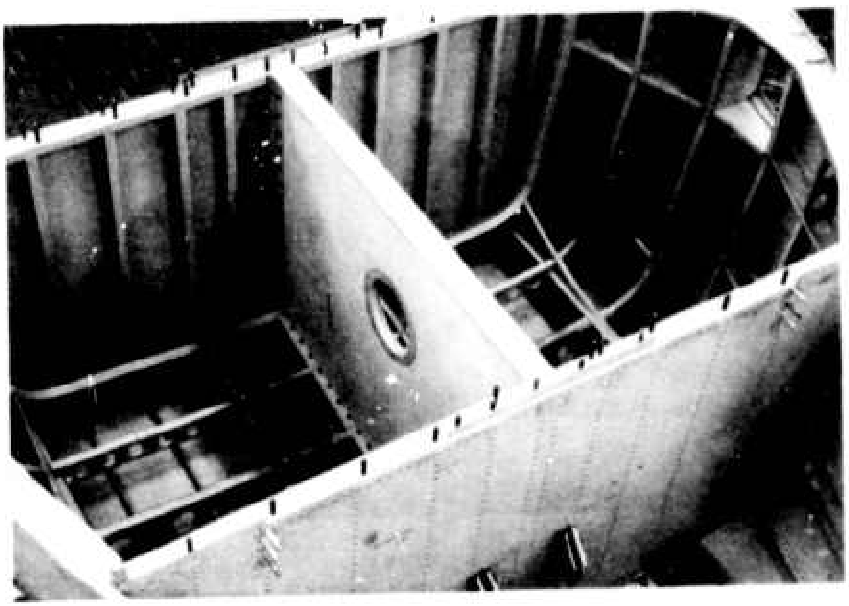

Figure 4. Fuel Cell Structure

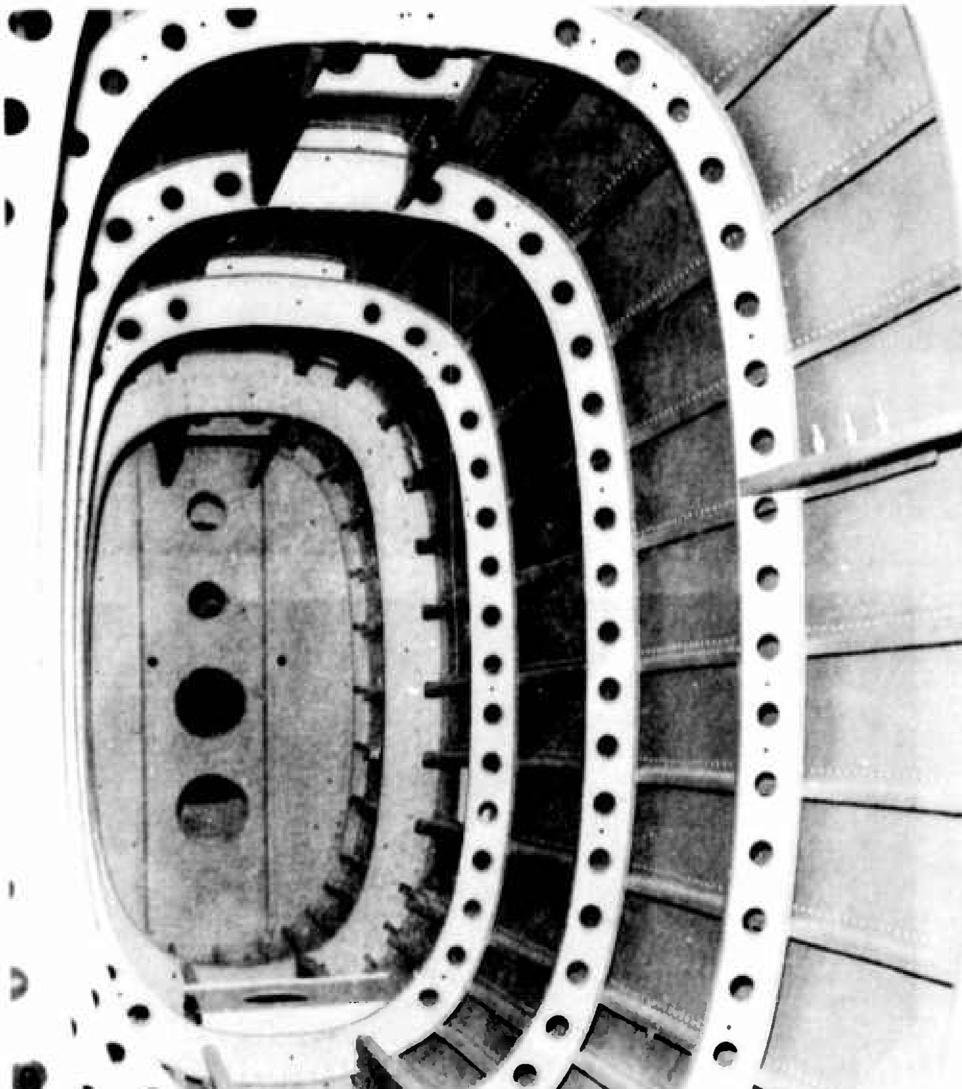

Figure 5. Tailcone Interior Structure

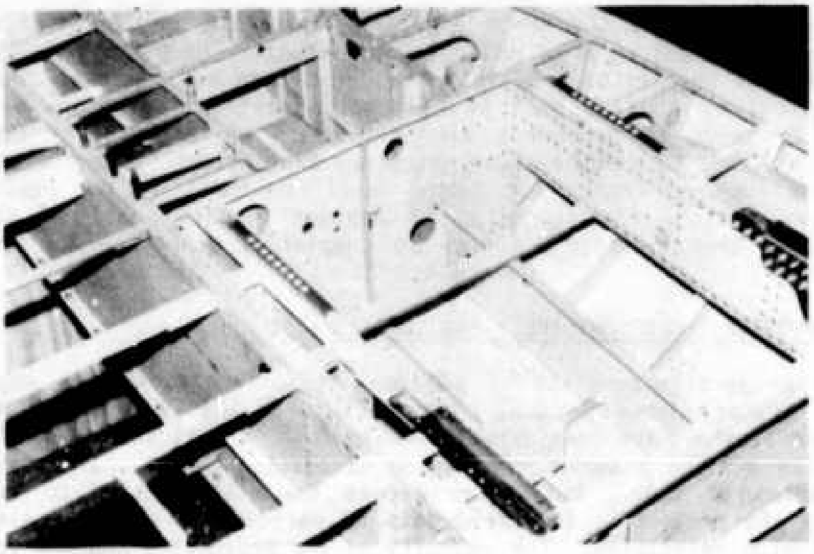

Figure 6. Forward Cabin and Cockpit Tub Structure

DESCRIPTION OF THE THREATS

ARMOR PIERCING INCENDIARY (API) PROJECTILES

These projectiles consist of a hard tough core, shaped to maximize penetrability, and a thermally active filler. The active filler is located in front of the passive core. Upon impact, the core penetrates the exterior of the target. This gives the projectile a fire-starting capability in the presence of flammable materials.

The damage caused by the armor piercing projectile is dependent on its mass, velocity, and angle of obliquity at impact. The primary damage is caused by the penetrator. Against the light skin and stringer construction typical of a large part of helicopter airframes, the low velocity projectile tends to produce cracks and tears while the high velocity projectile tends to produce clean entry and exit holes. Impact with heavy structure such as frames and beams usually results in the removal of irregular sections of material. At maximum velocity, all of the API projectiles have sufficient energy to completely penetrate any airframe structure.

HIGH EXPLOSIVE INCENDIARY (HEI) PROJECTILES

The HEI projectile consists of a time-varying fuze mechanism, explosive charge, tracer element, and an outer casing. Figure 7, reprinted from Reference 1, shows the configuration. The fuze is activated when the projectile strikes a surface, delaying detonation of the charge for varying lengths of time. Detonation causes the shell casing to rupture, breaking the projectile into fragments of various sizes and accelerating them to high velocities. The velocity of the projectile and the velocity of the fragments due to the explosive charge are combined vectorially. This has the effect of focusing the fragments into a cone (Figure 8). In addition to fragments, the explosive charge produces a shock wave which travels at high Mach numbers, initially preceding the accelerating fragments. Structures close to the point of detonation are prestressed by the shock wave and overpressure prior to impact by the fragments.

The effect of an HEI impact on metal airframe structure is highly dependent on the fuze mechanism and the configuration of the structure. For light skin and stringer construction, the projectile normally produces a relatively clean penetration on the entry side. The size of the hole typically is two times larger than the projected area of projectile. In an empty enclosed structure such as a tailcone, fragments generated by the

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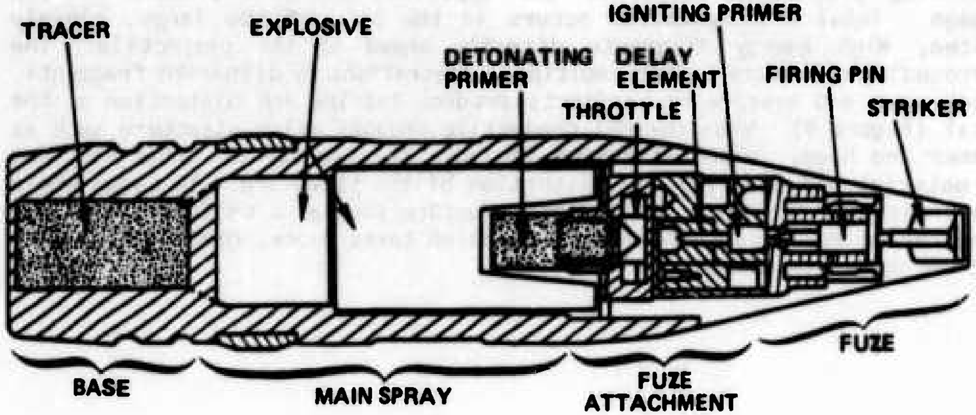
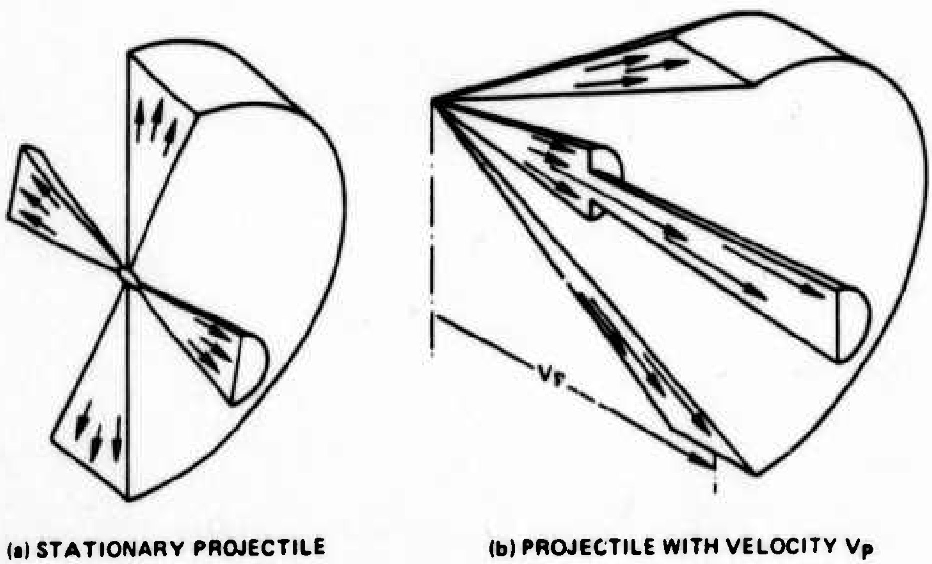
[1] Fitzpatrick, P. R., MODEL FOR THE PREDICTION OF EXPLOSIVE PROJECTILE DAMAGE TO AIRCRAFT STRUCTURES, Report No. UTRC-76-134, United Technologies Research Center, East Hartford, CT, August 1976.



* Reprinted from Reference 1.

Figure 7. Typical HEI Projectile



* Reprinted from Reference 1.

Figure 8. Fragmentation Patterns Associated with a Typical HEI Projectile

exploding projectile penetrate the opposite skin and produce massive damage. Total disintegration occurs in the path of the large, closely spaced, high energy fragments directly ahead of the projectile. The surrounding structure suffers multiple penetrations by dispersed fragments. Shock wave and overpressure effects produce tearing and distortion of the metal (Figure 9). When the HEI projectile engages major structure such as frames and beams, expected damage includes the removal of large sections of material and buckling and distortion of the structure. In cases where the projectile impacts a thin light structure such as a tail fin, complete penetration may occur before the explosion takes place, greatly diminishing the damage sustained.

Figure 9. Exit-Side Damage Caused by the HEI Projectile

SHOTLINE SIMULATION

One requirement of this program was to assess the structural effects of ballistic damage to the Black Hawk helicopter airframe resulting from typical impacts by API and HEI projectiles.

Selecting a representative population of ballistic strikes on the airframe was considered essential to making a realistic assessment of combat damage. It was felt that results could be very misleading if the study were based on an arbitrary selection of critical damage conditions. For example, while a large caliber API penetration of the transmission support structure from directly above might represent a critical type of combat damage, it is a relatively improbable event. Similarly, because of variations in area vulnerability and the effects of masking, ballistic damage to certain other areas of the airframe is also unlikely. Cases such as these might be interesting candidates for structural analysis and repair concept development, but they would probably not be representative of the damage the aircraft would actually experience in combat.

The missions of helicopters in combat, the tactics they employ, and the threats they encounter make some types of ballistic strikes more probable than others. For example, against the threats generally postulated, it is expected that the helicopter will rarely receive hostile fire from above. Projectiles fired from directly beneath the helicopter also have a low probability. Data collected from helicopter combat operations in Southeast Asia show the sides of the helicopter in the lower quadrant to be most vulnerable (Figure 10). Against a more sophisticated enemy force and a different threat mix and density, the vulnerable areas of the aircraft would probably be distributed differently. For example, attack helicopters operating at low altitudes and long standoff ranges are probably more vulnerable to frontal and top hits than were aircraft operating in Viet Nam. And aircraft in terrain-following and nap-of-the-earth (NOE) flight are probably more exposed to strikes in the upper hemisphere than were aircraft flying at altitude over jungles in Southeast Asia.

SHOTLINE SIMULATION MODEL

When the altitude and attitude of the aircraft are considered together with the possible locations of and distances to the threat, it is clear that there exists a limitless number of potential strikes on the airframe, each varying with respect to the precise point of impact and the aspect of the shotline in azimuth and elevation. Selection of a small population of strikes for analysis could become very subjective. To eliminate bias in the selection, it was decided to develop a computer model for generating random shots on the airframe. Key variables included in the model are shown in Figure 11. Conventions with respect to azimuth angle and elevation angle are given in Figure 12.

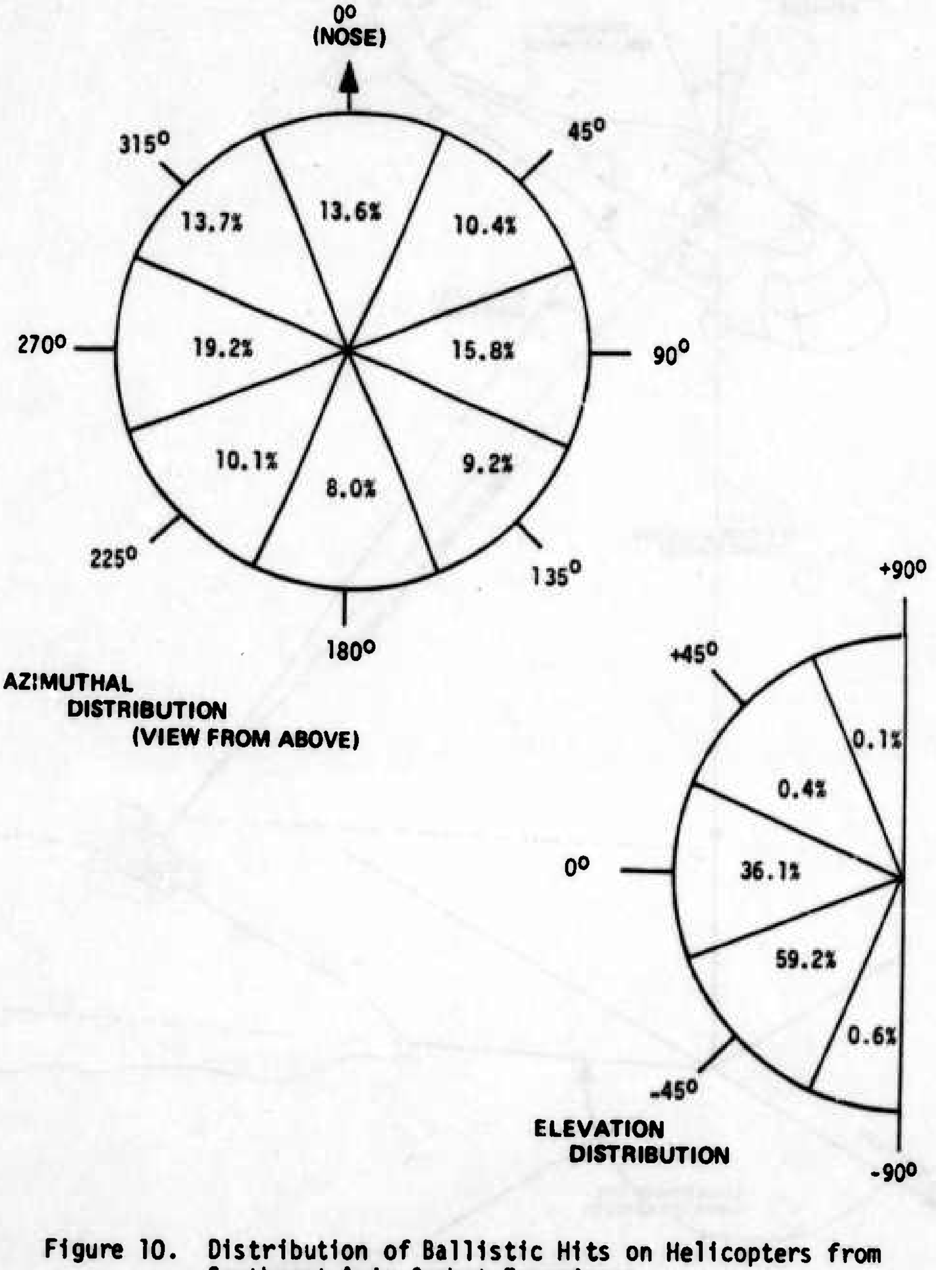


Figure 10. Distribution of Ballistic Hits on Helicopters from Southeast Asia Combat Experience

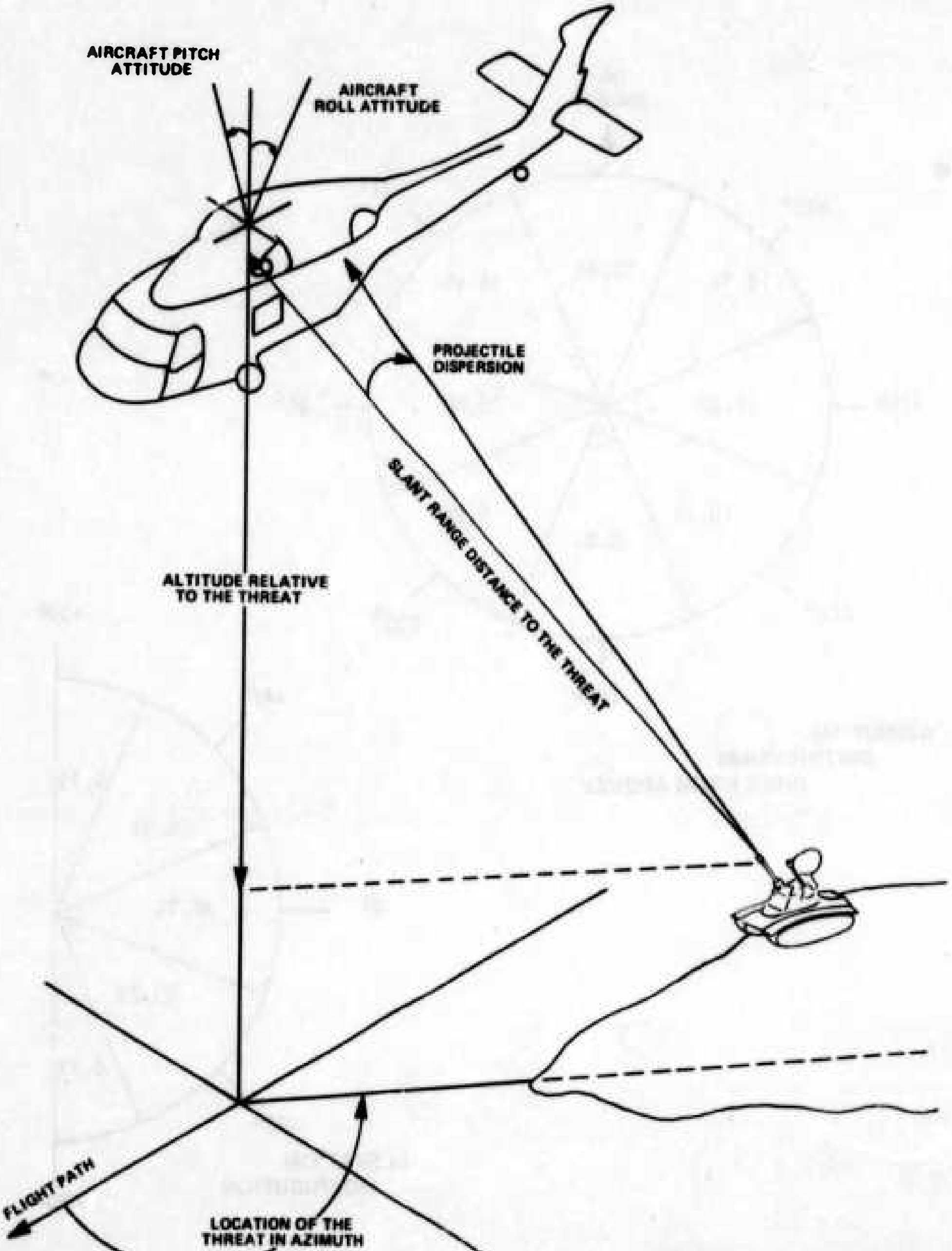


Figure 11. Shotline Simulation Model

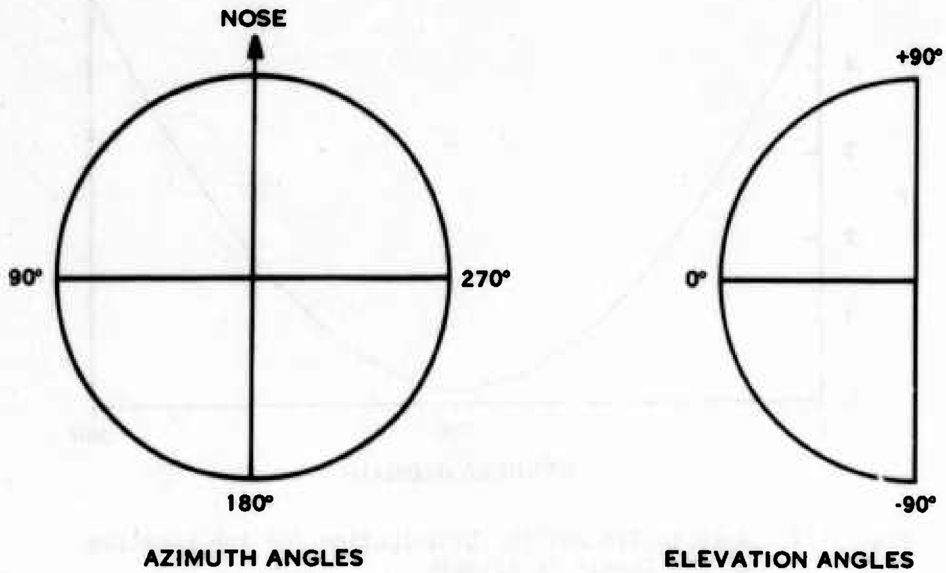


Figure 12. Conventions for Azimuth and Elevation Angles

Location of the Threat in Azimuth

The Black Hawk helicopter will be employed primarily in airmobile operations where it will be used to assault, reposition, and laterally move units along the forward edge of the battle area (FEBA). For purposes of the shotline simulation model, it was assumed that the aircraft would be most likely to engage hostile fire from the front as it moved toward the enemy's defenses and that the probability of a hit would decline with rotation in azimuth toward the rear of the aircraft. A direct tail shot was assumed to be least likely. The distribution assumed for location of the threat in azimuth is shown in Figure 13. The distribution by planform sectors is shown in Figure 14. Agreement is quite close to the historical distribution of hits on helicopters operating in Southeast Asia shown earlier in Figure 10.

Aircraft Altitude Relative to the Threat

In the future conflicts generally postulated, the Black Hawk will be threatened by sophisticated forces and automated fire control systems. To avoid detection and attack, the aircraft will employ terrain-following and NOE flight, taking maximum advantage of the terrain and natural concealment. For the purposes of the shotline simulation, it was assumed that the aircraft would be operating at a mean altitude of 100 feet relative to

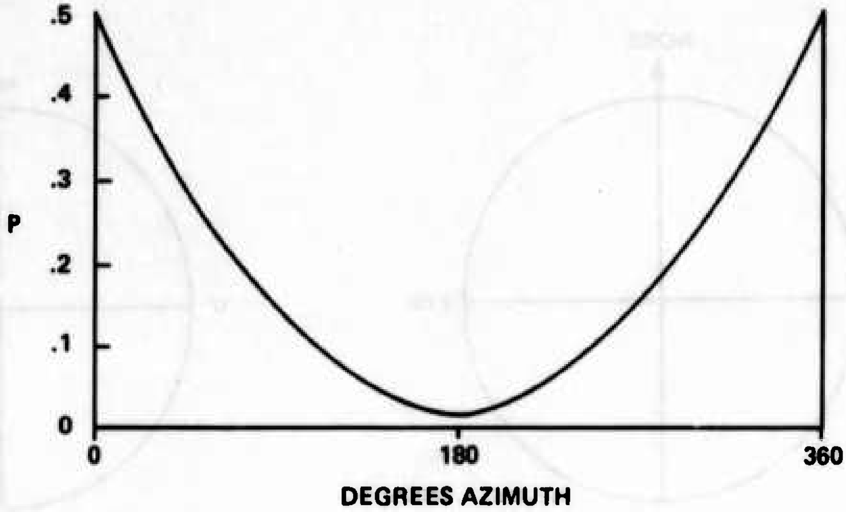


Figure 13. Assumed Probability Distribution for the Location of the Threat in Azimuth

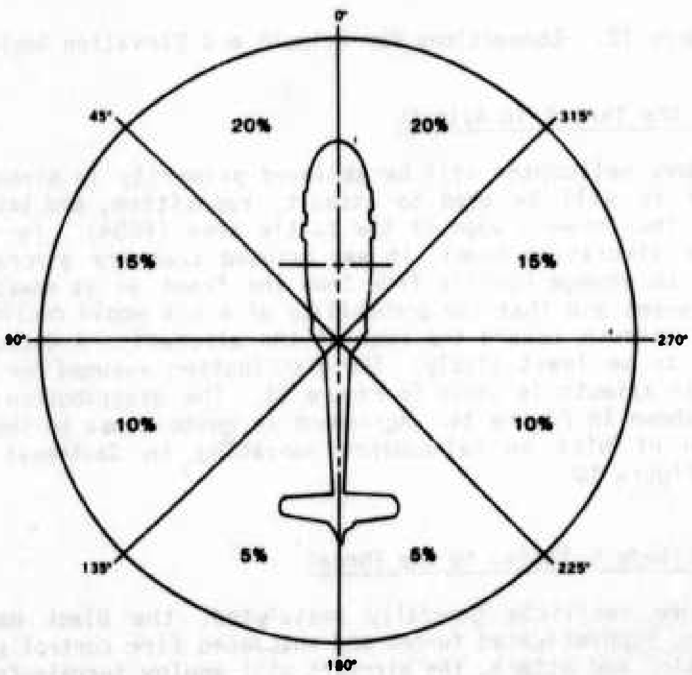


Figure 14. Assumed Distribution of Threat Location by Planform Sectors

the ground-based threat (Figure 15). The standard deviation in altitude was assumed to be 50 feet. This implies that 2% of the time the aircraft will be flying below a threat situated on elevated terrain. Only 2% of the time would the aircraft be operating at an altitude of 200 feet or more above the threat.

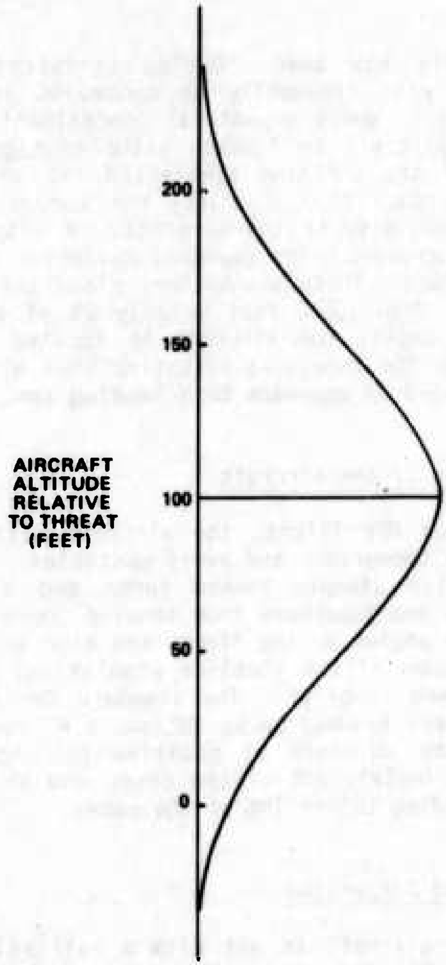


Figure 15. Assumed Distribution of the Aircraft Altitude Relative to the Threat

Slant Range Distance to the Threat

It was a requirement of the program to analyze airframe combat damage relative to four primary threats. The average distance at which the helicopter will be engaged by a given threat will depend in part on the effective range of the weapon. Slant range distances will tend to be lower for the smaller caliber weapons and higher for the larger caliber weapons. To keep the modeling within the scope of the program, it was necessary to select a distribution of slant range distances that would be reasonable for all threats.

The following rationale was used: During terrain-following and NOE flights, the aircraft will frequently be concealed from the threat by terrain and ground cover. Where no natural concealment exists, the horizon will obscure the aircraft to threats situated significant distances away. For purposes of the shotline simulation, it was assumed that in order to detect and attack the aircraft, the threat would have to be situated in relative proximity to the aircraft. A mean slant range distance of 900 feet was assumed. The standard deviation of the slant range was assumed to be 300 feet. These assumptions place the threat at a slant range distance of more than 1,500 feet in only 2% of the cases. In approximately 5% of the cases, the aircraft is located within a 500-foot slant range distance to the threat, a situation that might be encountered when the threat is engaged on approach to a landing zone.

Pitch and Roll Attitudes of the Aircraft

In terrain-following and NOE flight, the aircraft will undergo frequent maneuvers to follow the topography and avoid obstacles. Under some conditions, this will involve steeply banked turns and high aircraft roll angles. Rapid entry to and departure from landing zones will position the aircraft at steep pitch angles during flares and high acceleration forward transitions. For purposes of the shotline simulation, the mean roll and pitch angles were assumed to be 0°. The standard deviations of the roll angle and pitch angle were assumed to be 35° and 5.8° respectively. These assumptions position the aircraft at positive or negative roll angles exceeding 45° in approximately 20% of the cases and at positive or negative pitch angles exceeding 10° in 10% of the cases.

Projectile Aim Point and Dispersion

The point at which an aircraft is hit with a ballistic projectile will depend on the weapon; the method of fire control (radar, visual); the specific point at which the gunner aims; and errors introduced by the accuracy of the weapon, the distance to the target, the speed and direction of the target, evasive maneuvers by the pilot, and weather conditions (visibility, wind, temperature, etc.).

Evaluating these variables can involve a very complex modeling exercise. Since the objective of this study was not to assess the probability of taking a hit, but rather to obtain a realistic sample of hits, for simplification it was assumed that the gunner has a clear view of the aircraft, that he aims for a critical point on the aircraft (approximately the center of the main transmission), and that he is sufficiently skilled to account for the speed and direction of the aircraft. To introduce randomness in the sample of hits, the shot was assumed to be displaced from the aim point by a mechanical inaccuracy in the weapon. Weather factors were ignored. A mean inaccuracy of 0 mils and a standard deviation of .005 times the slant range distance were assumed. The shot was assumed to be displaced in a radial direction from the aim point, the angle of which was assumed to be random.

Impact Point Projection

The point of impact was projected onto one of three perpendicular cutting planes intersecting at the main transmission (Figure 16). Table 1 gives the criteria for selecting the plane of projection.

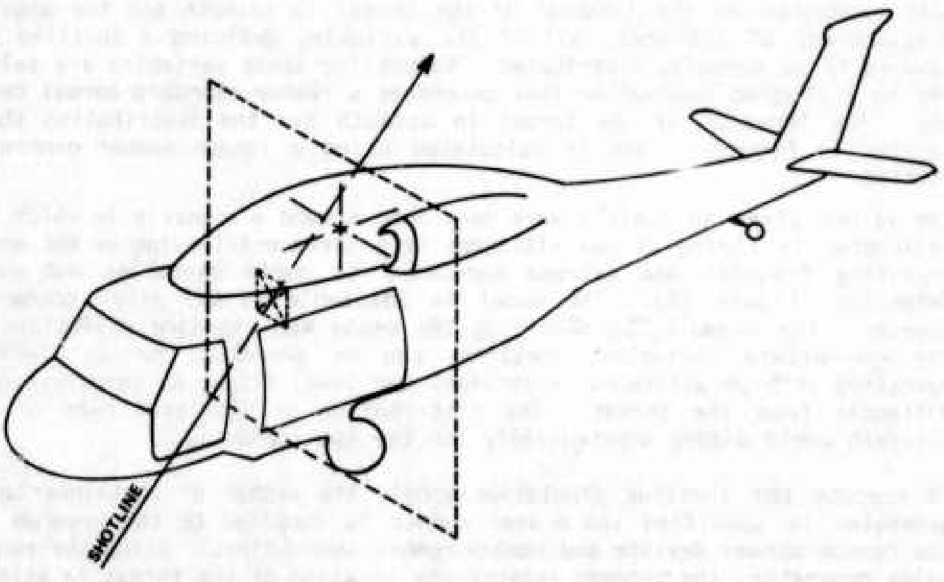


Figure 16. Projection of Shotlines Onto Cutting Planes

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TABLE 1. IMPACT POINT PLANES OF PROJECTION		
Elevation Angle (Deg)	Azimuth Angle (Deg)	Plane of Projection
+46 - +90 -46 - -90	All	Waterline
-45 - +45	1 - 45 136 - 225 316 - 360	Station
	46 - 135 226 - 315	Butt Line

Shotline Model Logic

The shotline simulation model was programmed for operation on an IBM 370 computer. The program logic is shown in Figure 17. As shown in Table 2, with exception of the location of the threat in azimuth and the angular displacement of the shot, all of the variables defining a shotline are assumed to be normally distributed. Values for these variables are selected by a program subroutine that generates a random standard normal deviate. The location of the threat in azimuth has the distribution shown earlier in Figure 13 and is calculated using a random number generator routine.

The values given in Table 2 were developed around a scenario in which the helicopter is flying at low altitudes in a terrain-following or NOE mode, executing frequent and extreme maneuvers to avoid obstacles and evade detection (Figure 18). The model is adaptable to any other scenario, however. For example, by modifying the means and standard deviations of the appropriate variables, shotlines can be generated for an aircraft operating at high altitudes in straight and level flight at large standoff distances from the threat. The distribution of simulated hits on the aircraft would differ substantially for the two scenarios.

To execute the shotline simulation model, the number of shotlines to be generated is specified and a seed number is supplied to the program for the random normal deviate and random number subroutines. Using the random value generator, the program selects the location of the threat in azimuth and the altitude of the aircraft relative to the threat. Next, a random slant range distance to the threat is generated. If the combination of altitude and slant range places the weapon within 100 feet of the aircraft, another slant range distance is generated. The random value generators are then used to select the pitch and roll attitudes of the aircraft in flight. If the roll angle exceeds ± 90° or the pitch angle exceeds ± 15°, a new random value for the respective angle is generated.

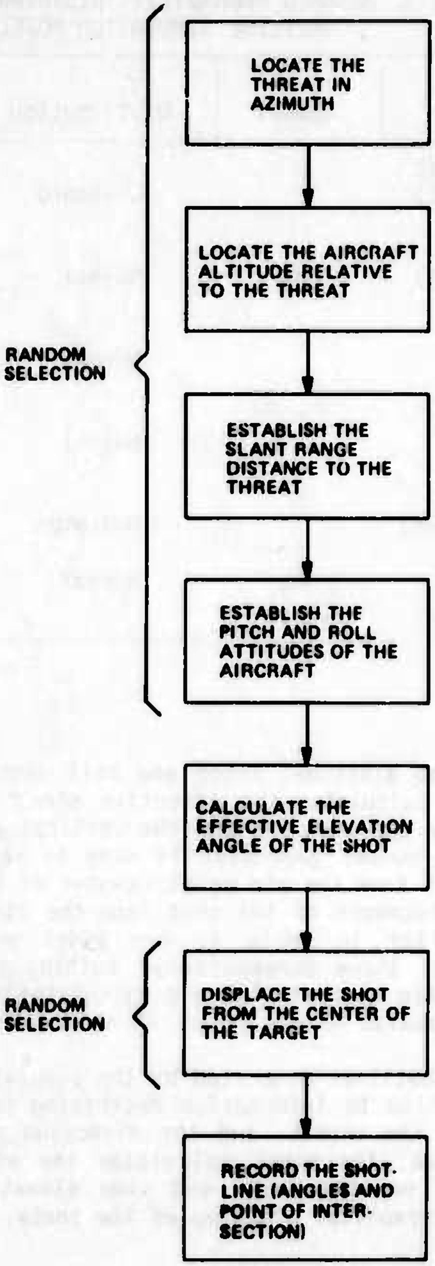

Figure 17. Shotline Model Logic

TABLE 2. ASSUMED PROBABILITY DISTRIBUTIONS FOR THE SHOTLINE SIMULATION MODEL				
Variable	Symbol	Distribution	Mean	Std. Dev.
Location of the Threat in Azimuth (Degrees)	α	U-Shaped	(See Figure 4)	
Slant Range Distance To the Threat (Feet)	d_1	Normal	900	300
Aircraft Roll Angle (Degrees)	ρ	Normal	0	35
Aircraft Pitch Angle (Degrees)	ϕ	Normal	0	5.8
Angular Displacement of the Shot (Degrees)	θ	Uniform	$(0 \leq \theta \leq 360)$	
Linear Displacement of the Shot (Feet)	d_2	Normal	0	$.005(d_1)$

Based on the selected altitude, pitch and roll attitude, and slant range distance, the model calculates the effective elevation angle of the shot (the angle formed by the shotline and the vertical centerline of the aircraft). The random number generator is used to select the angular displacement of the shot from the aim point (center of the main transmission) and the linear displacement of the shot from the aim point. Based on the criteria shown earlier in Table 1, the model projects the displaced shotline onto one of three perpendicular cutting planes intersecting at the center of the main transmission and calculates the Station, Waterline, and Butt Line coordinates of the point at which the plane is penetrated.

A sample of random shotlines generated by the simulation model is shown in Figure 19. In addition to information describing the calculated location of the aircraft and the threat, and the direction and point of intersection of the shotline, the model calculates the effective angle of the shotline as viewed from the front and side elevations of the aircraft. These were used for graphical plotting of the shots.

Figure 18. Black Hawk Helicopter in Nap-of-the-Earth Flight

** HELICOPTER SHOT LINE LOCATIONS **

	CASE NUMBER									
	11*	12*	13*	14*	15*	16*	17*	18*	19*	20*
LOCATION OF AIRCRAFT RELATIVE TO THREAT :										
AZIMUTH(ALPHA),DEG =	280	34	72	198	229	308	319	304	339	243
ELEVATION(EPSILON),DEG =	-2	-12	-6	-8	-4	-6	-4	-4	-5	-6
ALTITUDE,FEET =	72	131	101	112	98	163	89	95	106	108
SLANT RANGE,FEET =	1236	601	864	684	1225	1419	1123	997	1039	950
AIRCRAFT ATTITUDE RELATIVE TO INERTIAL COORDINATES :										
PITCH ANGLE(PHI),DEG =	6	-7	-7	15	0	2	-1	-2	6	-6
ROLL ANGLE(RHO),DEG =	-18	6	-11	-3	37	-50	-58	19	3	11
SHOT LINE INTERSECTION RELATIVE TO TRANSMISSION CUTTING PLANES :										
STATION LINE =	326	341	346	341	362	344	341	334	341	304
WATERLINE =	282	282	264	261	314	259	258	254	217	329
BUTT LINE =	0	5	0	13	0	0	18	0	-22	0
SHOT LINE ENTRANCE ANGLES :										
AZIMUTH(ALPHA),DEG =	280	34	72	198	229	308	319	304	339	243
EFFECTIVE ELEVATION,DEG										
ALONG SHOT LINE =	17	-15	-20	-22	-31	35	32	-21	-1	-12
FRONT =	17	-26	-21	-53	-39	42	44	-25	-4	-13
SIDE =	61	-18	-51	-23	-43	49	60	-36	-1	-25

Figure 19. Sample Shotline Model Output

SHOTLINE GENERATION AND CASE SELECTION

The shotline model was used to generate 150 random shots on the Black Hawk helicopter airframe. Each of the 150 shotlines was plotted on the three principal views of the aircraft as shown in Figure 20. The 150 plotted shotlines were reviewed and 59 of them were selected for detailed analysis. Shotlines were selected to provide a sample of cases for each of the six major sections of the airframe (cockpit, cabin, transition section, tailcone, pylon, and stabilator). Within each section, only those shotlines appearing to involve primary airframe structure were considered for selection.

SHOTLINE MODELING

The FASTGEN computer model and the Black Hawk target description (References 2 and 3) were used to trace the path of the selected shotlines through the Black Hawk helicopter and to calculate the points and angles of intersection with each component and piece of structure encountered along each shotline. The FASTGEN model uses a geometric description of the helicopter called a COM-GEOM (combinatorial geometry) target description. COM-GEOM is a method of creating a three-dimensional representation of a vehicle (aircraft, tank, etc.) from a set of elementary solids (cubes, cones, etc.) described in a Cartesian coordinate system. Each component and element of structure in the aircraft, together with spaces within and between them, are represented as one or more of these elementary solids. Solids are combined using set theory operations to approximate the basic shapes of the objects. Dimensions, locations, and orientations are specified in a common coordinate system. Figure 21 is a computer graphics representation of the Black Hawk helicopter drawn by FASTGEN from the COM-GEOM target description.

The 59 selected cases were prepared for input to the FASTGEN model. Station, Waterline, and Butt Line coordinates identifying the point through which each shotline passes were translated into the FASTGEN coordinate system.

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[2] Ullyatt, L. G., Thompson, J. P., and Smith, L. E., TARGET DESCRIPTION FOR SURVIVABILITY/VULNERABILITY ASSESSMENT, Volume I, GEOMETRIC MODELING FOR FASTGEN (DRAFT), Falcon Research and Development Company; Report No. TR-33800, Naval Weapons Center, China Lake, CA, May 1978.

[3] Belote, C. E., and Severance, J. D., FASTGEN II TARGET DESCRIPTION COMPUTER PROGRAM, Booz, Allen and Hamilton, Inc.; Report No. JTCG/AS-78-V-002, The Joint Logistics Commanders Joint Technical Coordinating Group on Aircraft Survivability, Naval Air Systems Command, Washington, DC, January 1980.

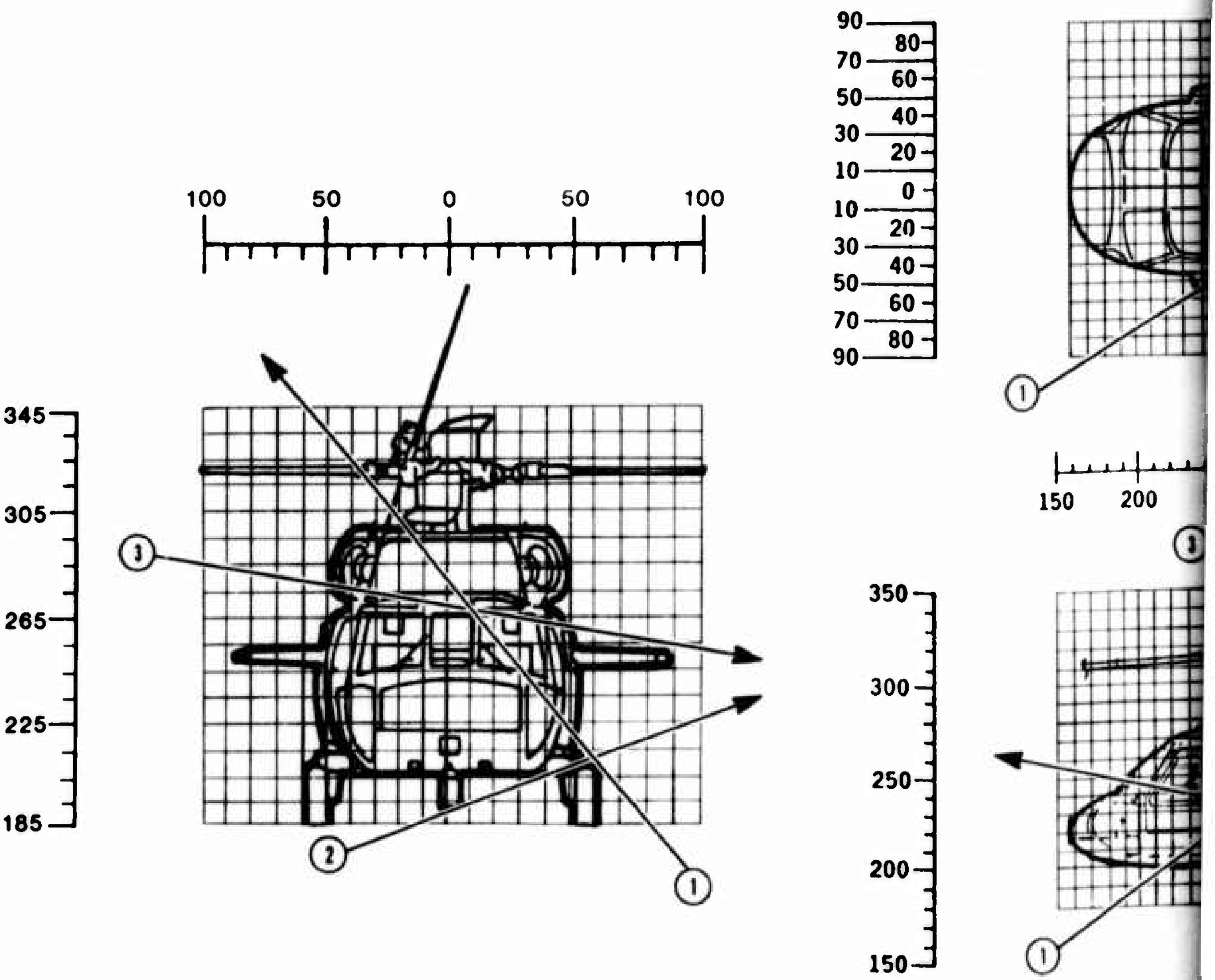
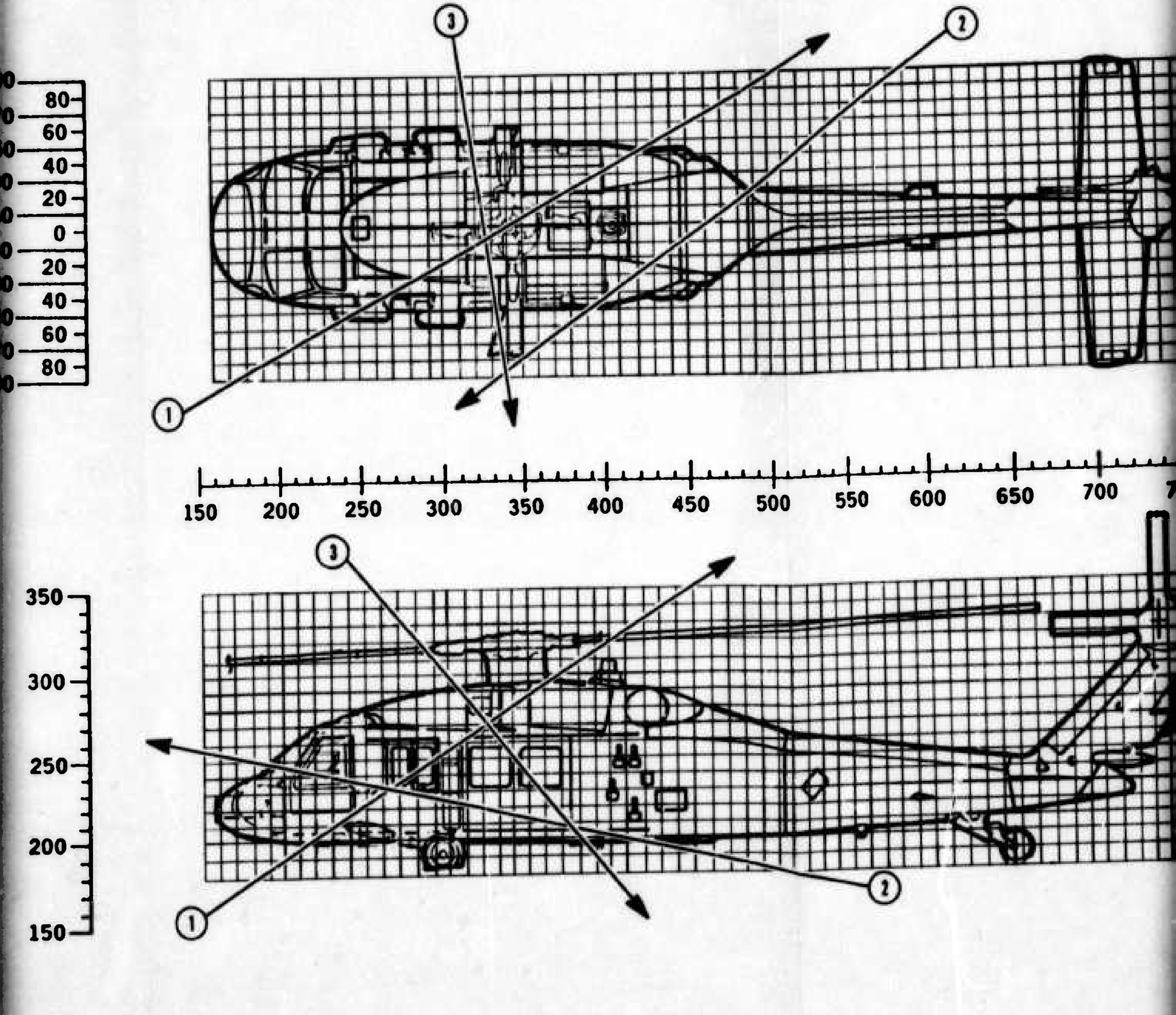


Figure 20. Graphical Plotting of Shotlines on the Principal Views of the Aircraft



1
2
3
80
60
40
20
0
20
40
60
80
150
200
250
300
350
400
450
500
550
600
650
700
1
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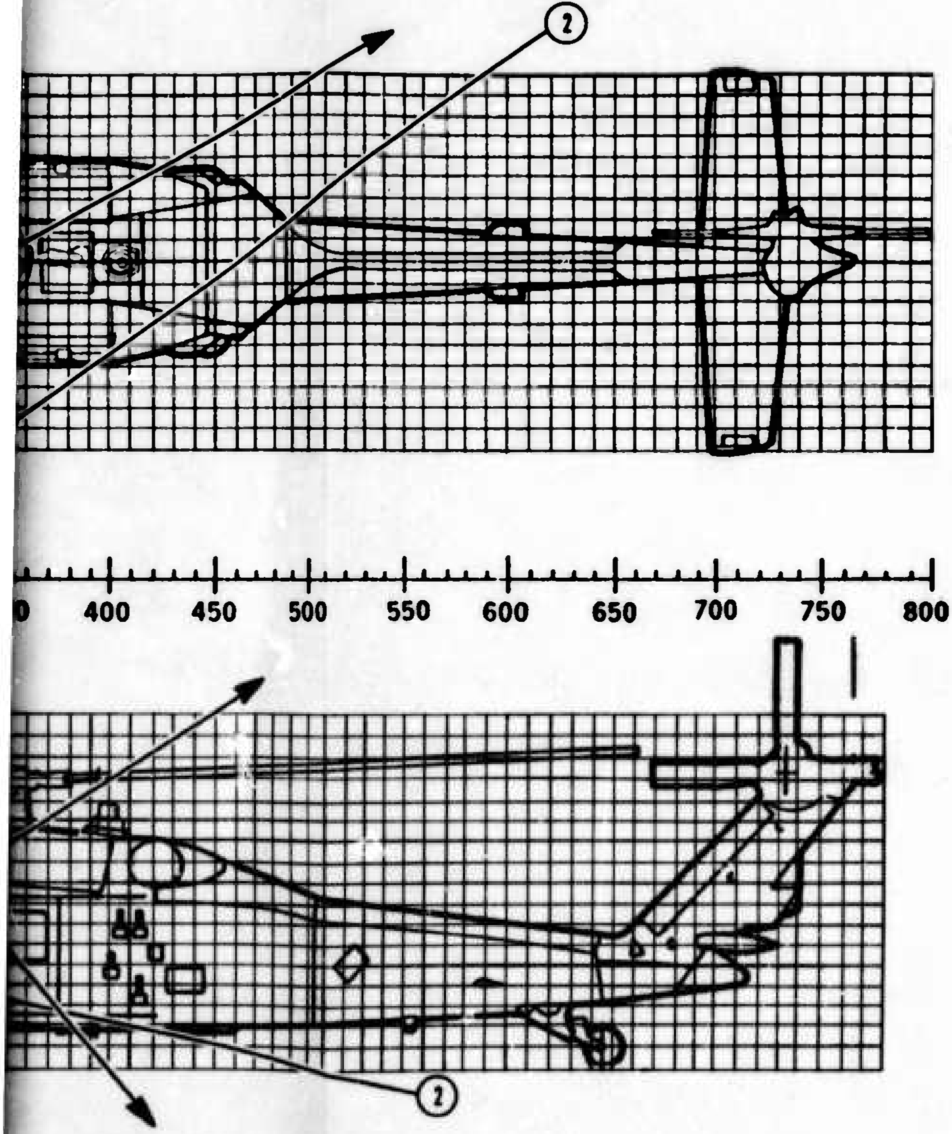
350
300
250
200
150


2
400
450
500
550
600
650
700
750
800
2

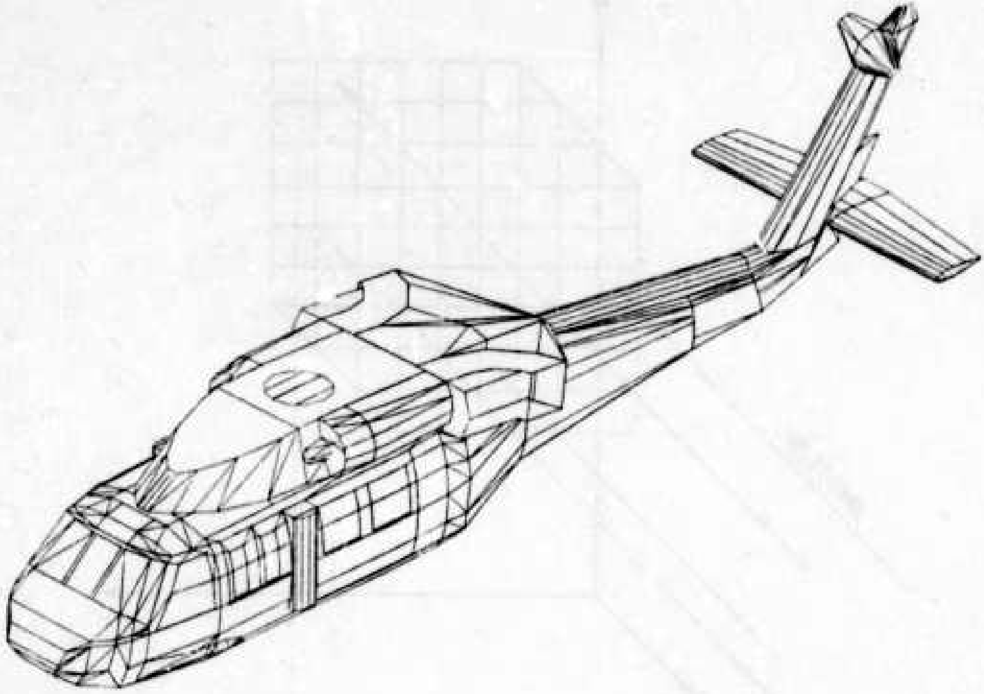


Figure 21. Computer Drawing of the Black Hawk Helicopter Using the FASTGEN Model and the Black Hawk COM-GEOM Target Description

The graphical plots of the shotlines from which the 59 cases were selected (Figure 20) provided a reasonable indication that the path of each shotline would carry it through one or more elements of primary airframe structure. However, the plots were not accurate enough to be certain of this. Small displacements from the plotted path might be sufficient to cause none of the primary airframe structure to be intersected. To increase the likelihood that each of the selected cases would involve primary structure as desired, FASTGEN was programmed to generate multiple shotlines through presented surfaces of a 6-inch cube enveloping the specified aim point (Figure 22). Within FASTGEN, the defined cube is aligned with the principal axes of the helicopter and a 1-inch grid is overlaid on the surfaces of the cube presented to the line of sight. FASTGEN runs parallel shotlines through the center of each cell. Depending on the presented surface area of the cube, as many as 85 shotlines were generated for a single case.

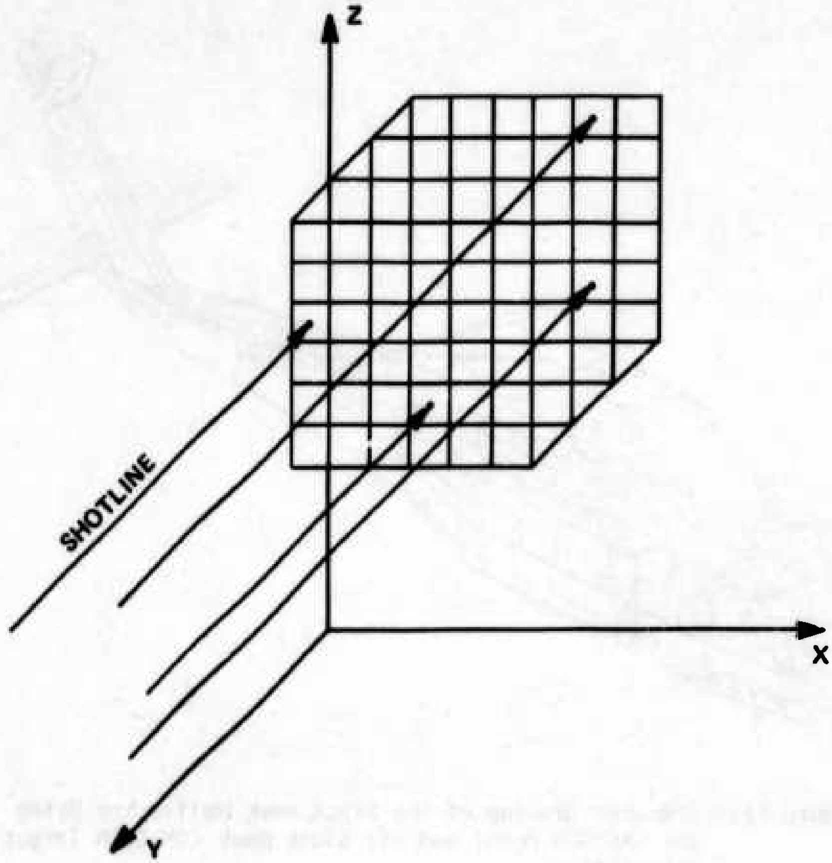


Figure 22. Shotlines Projected Onto a 6-Inch Cube Enveloping the Aim Point

A sample of the output from the FASTGEN model is shown in Figure 23, identifying the selected elements of output used for this program. The number in the upper left corner of each block of data identifies the sequential order of the shotlines generated for each case. The Y' and Z' values listed at the top of each block of data fix two of the coordinates for the shotline in the FASTGEN coordinate system. The first column of numbers in the block lists codes identifying specific aircraft components and elements of structure intersected along the shotline. The next two columns of numbers list the X' coordinate (moving down the shotline) at which the initial surface of each component is intersected and the apparent thickness of the component or structure as viewed along the line of sight. In the second to last column is listed the secant of the obliquity angle (angle of the shotline relative to the surface of the part). Other data contained in the FASTGEN output was not used.

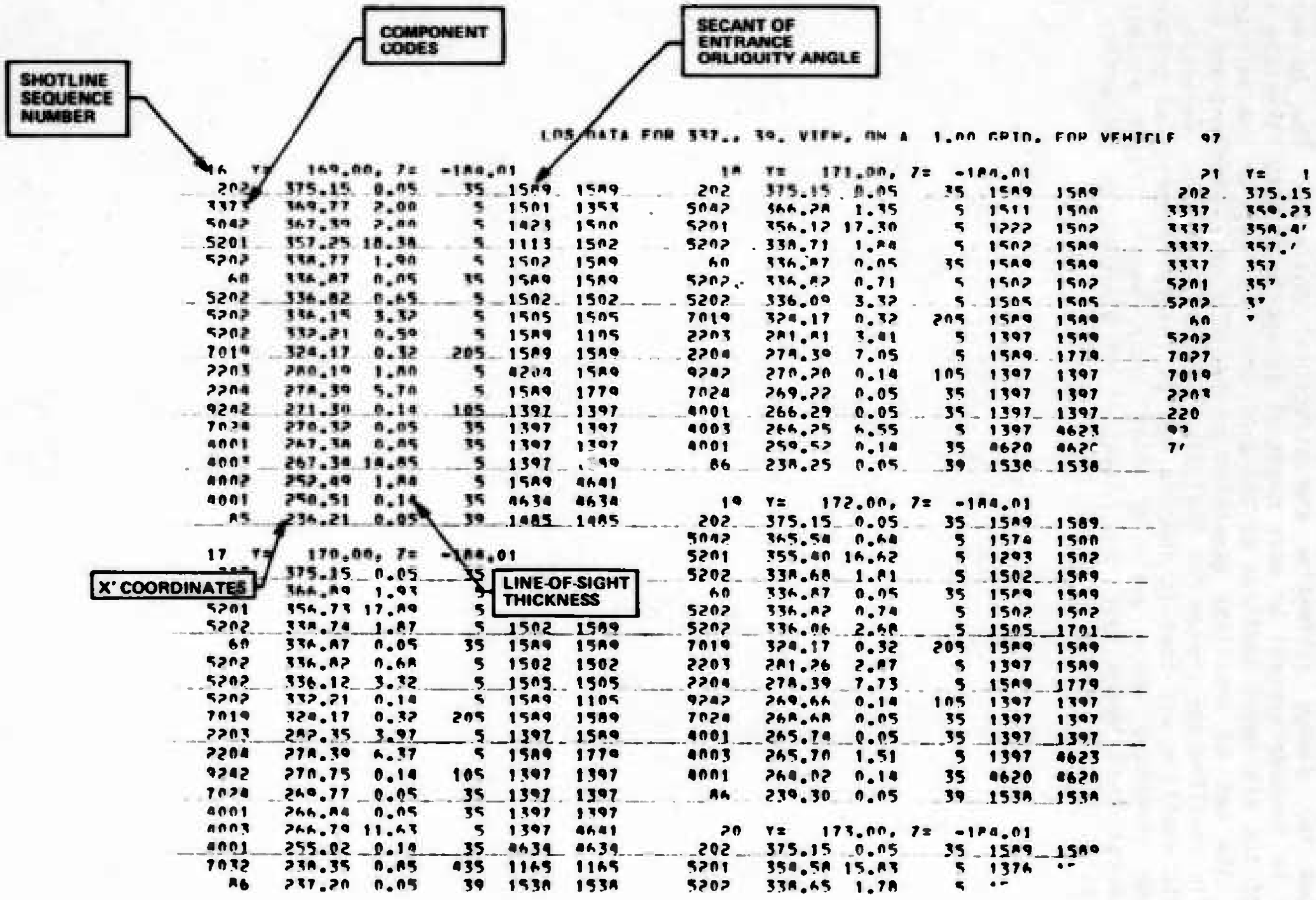


Figure 23. Sample FASTGEN Model Output

SHOTLINE SELECTION

The FASTGEN outputs for the 59 cases were analyzed and 40 cases were selected for damage estimation and structural analysis. The 40 were chosen to include several or more cases of damage to primary structure in each of the six major sections of the airframe. For each of the selected cases, the set of shotlines generated by FASTGEN were examined and one specific shotline was chosen for analysis. The criterion for selecting a specific shotline was that it involve one to several elements of primary airframe structure while avoiding other large masses (major aircraft components) that would have the potential of stopping or deflecting a projectile.

API DAMAGE DESCRIPTIONS

In the next task of the program, API damage descriptions were developed for the 40 cases selected from the FASTGEN modeling. This involved calculating the extent of penetration of the projectile through the aircraft components and structure located along the shotlines analyzed by FASTGEN. For each item of airframe structure penetrated or impacted by the projectile, the size of the expected damage was calculated. Figure 24 shows the format used to conduct the analysis.

In the first set of blocks at the top of Figure 24, the projectile type, mass, and striking velocity were recorded. The striking velocity was calculated from the muzzle velocity of the weapon and the average velocity decay over the slant range distance generated by the shotline model. In the next set of blocks, the coordinates of the shotline were recorded. The azimuth and elevation angles and the Station, Waterline, and Butt Line coordinates of the aim point were obtained from the shotline model output. The Y' and Z' coordinates were obtained from the FASTGEN model output.

The aircraft components and airframe structure located on the shotline by FASTGEN were recorded in the designated columns of the worksheet (Figure 24) together with the following FASTGEN outputs:

Line-of-Sight (LOS) Thickness

Striking Obliquity (Secant of)

X' Coordinate

The material composition of each component and piece of structure was listed, and an estimate was made of the thickness of an equivalent plate of solid material, based on the configuration and internal geometry of each item.

PENETRATION ANALYSIS

Three computer programs used for ballistic penetration analysis were obtained from the Naval Weapons Center at China Lake, California. Based on the THOR equations, the programs analyze the penetration of projectiles against solids, fragments against solids, and projectiles through fluids.

Variables specified by the user include the striking velocity, yaw angle, and impact velocity of the projectile and a description of the target material and thickness. Target materials include aluminum, steel, and titanium. Fluid targets are specified at a specific density. The program calculates the ballistic limit velocity for the target (velocity needed to penetrate) and determines if the target is penetrated or the projectile is stopped or deflected. If penetration occurs, the residual mass and velocity of the projectile are calculated.

Case Number	
52	31

Projectile		
Type	Mass	Velocity
API	2550	2813

Shot Line Coordinates						
Azimuth Angle	Elevation Angle	Sta.	B.L.	W.L.	Y'	Z'
34	-24	341	-10	233	-241.01	169.01

Component/Structure	Code	Material	Thickness		Projectile Impact				Damage			
			LOS	Equiv. Plate	Velocity (fps)	Obliquity (sec)	Mass (gr)	X' Location	Lateral Dimension	Location Sta.	Location B.L.	Location W.L.
Skin, Bottom, Cabin	61	11	0.07	0.07	2813	2.458	2550	379.6	1.3	282.8	32.5	200.0
Beam, Long, Supt., Cabin Floor	7017	13	0.29	0.29	2791	1.957	2550	377.5	9.0	284.3	31.5	200.8
Cross Beam, Supt., Cabin Floor	7016	13	0.20	0.20	2407	1.320	1275	366.6	3.5	292.6	25.9	205.3
Floor, Cabin	7015	11	1.94	0.19	2341	2.458	1275	363.1	6.0	295.2	24.1	206.7
Skin, Side, Cabin	62	11	0.05	0.05	1963	1.534	1275	234.5	1.4	392.7	-41.6	259.0
Cowling, IR Suppress., Right	304	11	0.07	0.07	1953	2.399	1275	221.0	1.8	402.8	-48.5	264.5
Cowling, IR Suppress., Right	304	11	0.10	0.10	1883	3.336	1275	200.4	1.8	418.5	-59.0	272.9

Figure 24. Sample Penetration and Damage Size Analysis

The fragments analysis program treats fragments as cubes, spheres, diamonds, or parallelepipeds of user-specified size and weight. Input variables include the velocity and striking obliquity of the fragment and the target material and thickness. Permissible target materials include both metals and nonmetals. Like the projectiles program, the fragments program determines if the target is penetrated and calculates the residual mass and velocity of the fragment. Modifications were made to the projectiles against solids program to accept inputs in the format of the FASTGEN model output and to improve the printed documentation of the cases. Figure 25 shows the output of the modified projectiles against solids program.

The penetration analysis was conducted as follows: The striking velocity and initial mass of the projectile recorded at the top of the worksheet (Figure 24) were entered in the designated columns for the first target (component or item of structure) on the list. The material and thickness of the target were entered into the penetration analysis program, together with the mass, velocity, and striking obliquity of the projectile. A zero yaw angle was assumed. The program was run, and if a penetration of the target was effected, the residual mass and velocity of the projectile calculated by the program were entered as program inputs for the next target component or item of structure on the list. The process was continued until all targets on the list were penetrated or the program indicated that the projectile had been stopped or deflected from its path.

It was found that even with the high energy API projectiles, ricochets did occur when targets were struck at high obliquity angles. A ricochet in effect defines a new projectile path along which other airframe structure might or might not be engaged. To analyze these cases would have required calculating the angle of deflection, redefining the projectile path and rerunning the FASTGEN model. It is possible that one case could involve multiple ricochets and a very complex analysis. It was decided to terminate a projectile penetration analysis if a ricochet occurred. The alternative would have been to force a penetration of the surface causing the ricochet by arbitrarily reducing the obliquity angle. Whereas terminating the penetration ignores the possibility of additional airframe damage along the path of deflection, forcing the penetration would cause a definite distortion of the analysis and yield a combination of damaged elements and damage locations that probably would not occur in a real encounter.

```
       STRIKE
       VELOCITY = 2667.3                         CASE NO.  23 06
      ---------------------------------------------------------
      COMPONENT*RESIIUAL* ENTRANCE *  TARGET * TARGET   * PROJ
        CODE   *VELOCITY*  ANGLE   *  MATRL  *THICKNESS* MASS
      ---------------------------------------------------------
          201    2664.9        .77    2024-T4          .05 2550.0
           59    2628.2        .77    2024-T4          .14 1275.0
         7026    2530.3        .58    7075-T6          .36 1275.0
         7027     153.8       1.02    7075-T6          .57 1275.0
 RICOCHET ON CASE     23              8


       STRIKE
       VELOCITY = 3060.4                         CASE NO.  22 40
      ---------------------------------------------------------
      COMPONENT*RESIIUAL* ENTRANCE *  TARGET * TARGET   * PROJ
        CODE   *VELOCITY*  ANGLE   *  MATRL  *THICKNESS* MASS
      ---------------------------------------------------------
            2    3060.3        .16    2024-T4          .03 2550.0
         7004    3060.3        .15    2024-T4          .01 2550.0
         9802    2908.8       1.05    7075-T6          .31 2550.0
         9802    1798.7        .55    7075-T6         1.78 1275.0
         9803    1794.7        .57    7075-T6          .05 1275.0
            8    1674.7        .71    2024-T4          .25 1275.0


       STRIKE
       VELOCITY = 2751.5                         CASE NO.  21 43
      ---------------------------------------------------------
      COMPONENT*RESIIUAL* ENTRANCE *  TARGET * TARGET   * PROJ
        CODE   *VELOCITY*  ANGLE   *  MATRL  *THICKNESS* MASS
      ---------------------------------------------------------
            3    2750.1        .64    2024-T4          .05 2550.0
         3123    2749.6        .22    7075-T6          .06 1275.0
         7006    2491.3       1.06    7075-T6          .21 1275.0
         3123    2490.8        .22    7075-T6          .06 1275.0
         7004    2469.7        .51    7075-T6          .17 1275.0
         7008    2460.2        .51    7075-T6          .11 1275.0
            5    2454.9        .74    2024-T4          .05 1275.0


       STRIKE
       VELOCITY = 3114.9                         CASE NO.  19 15
```

Figure 25. Sample Penetration Analysis Program Output

DAMAGE SIZE ESTIMATES

The size of damage resulting from impact or penetration by a ballistic projectile is highly variable. Some of the key variables affecting damage size include:

Projectile-Related Factors

Mass

Diameter

Condition (from previous penetration)

Striking Velocity

Yaw Angle

Obliquity Angle

Target-Related Factors

Material (ductility, fracture toughness, etc.)

Configuration/Geometry

Thickness

Stiffening

Stress Level at Impact

Temperature at Impact

These factors affect not only the size of the damage but the mode of damage as well. The principal modes of damage for metal airframe structure include:

Cracks

Holes/Loss of Section

Spalls (front/rear)

Gouges

Petaling

Structural Deformation

After the penetration analysis was completed, an analysis was conducted to estimate the degree of damage to each item of airframe structure penetrated or impacted by the projectile. The Aircraft Structural Combat Damage Model Design Handbook published by the Air Force (Reference 4) was used to make these estimates. This handbook contains a series of curves that relate lateral damage to impact velocity and obliquity angle for projectiles against aluminum and titanium targets of from .032 inch to 1.0 inch thick. Figure 26 shows a typical curve. Both an upper and lower limit are given for the lateral damage at each set of conditions.

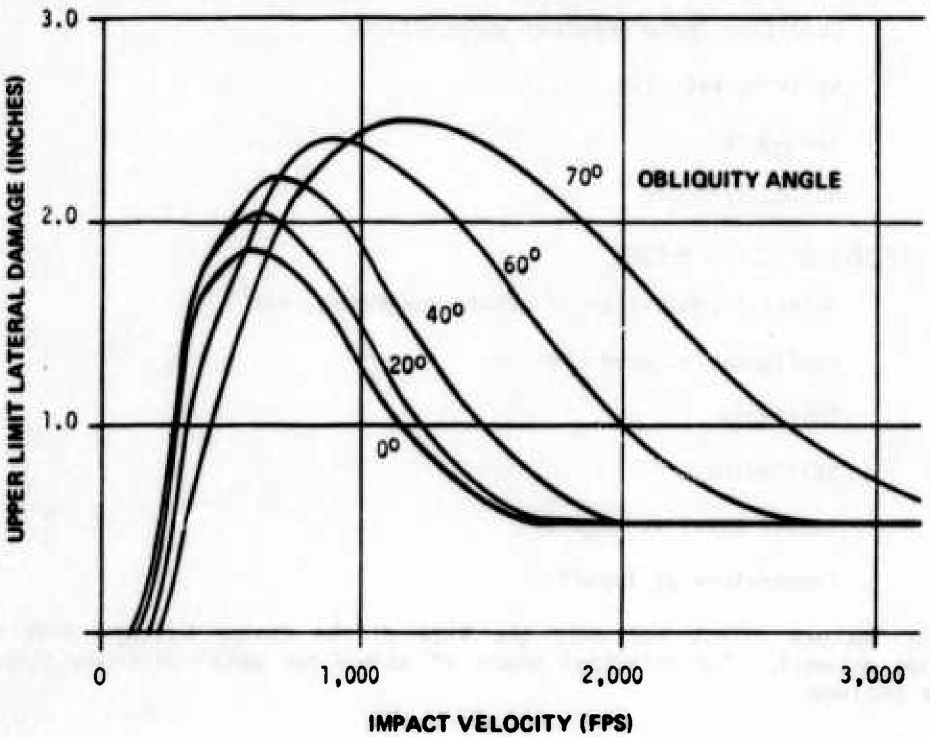


Figure 26. Sample Ballistic Tolerance Test Data Used to Calculate Damage Size

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4 Burch, G.T., Jr., and Avery, J.G., AN AIRCRAFT STRUCTURAL COMBAT DAMAGE MODEL-DESIGN HANDBOOK, The Boeing Company; Report No. AFFDL-TR-70-116, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, November 1970 (AD 877920).

Because the handbook does not cover the larger projectiles, it was necessary in some cases to extrapolate from the published curves. The damage sizes estimated for the airframe structure were recorded in the designated column of the worksheet.

The final step in completing the worksheet involved translating the FASTGEN model X', Y', Z' coordinates into Station, Waterline, and Butt Line coordinates to obtain exact points of impact for airframe structural elements. A computer program was written to effect the translations. The translated coordinates were entered in the last three columns of the worksheet.

API DAMAGE PLOTS

In the final task of the API damage description, detailed isometric drawings of the airframe were labeled to show the damaged elements and the locations and size of the damage. Figures 27 and 28 are typical examples. To facilitate plotting the locations of the airframe damage, a computer program was written to calculate the Station, Waterline, and Butt Line coordinates of points spaced any specified distance along the shotline. Figure 29 is a sample program output.

BALLISTIC DAMAGE DESCRIPTION

SHEET 1 OF 1

CASE NUMBER			PROJECTILE	STRIKING VELOCITY
15	4	32	API	2412.4

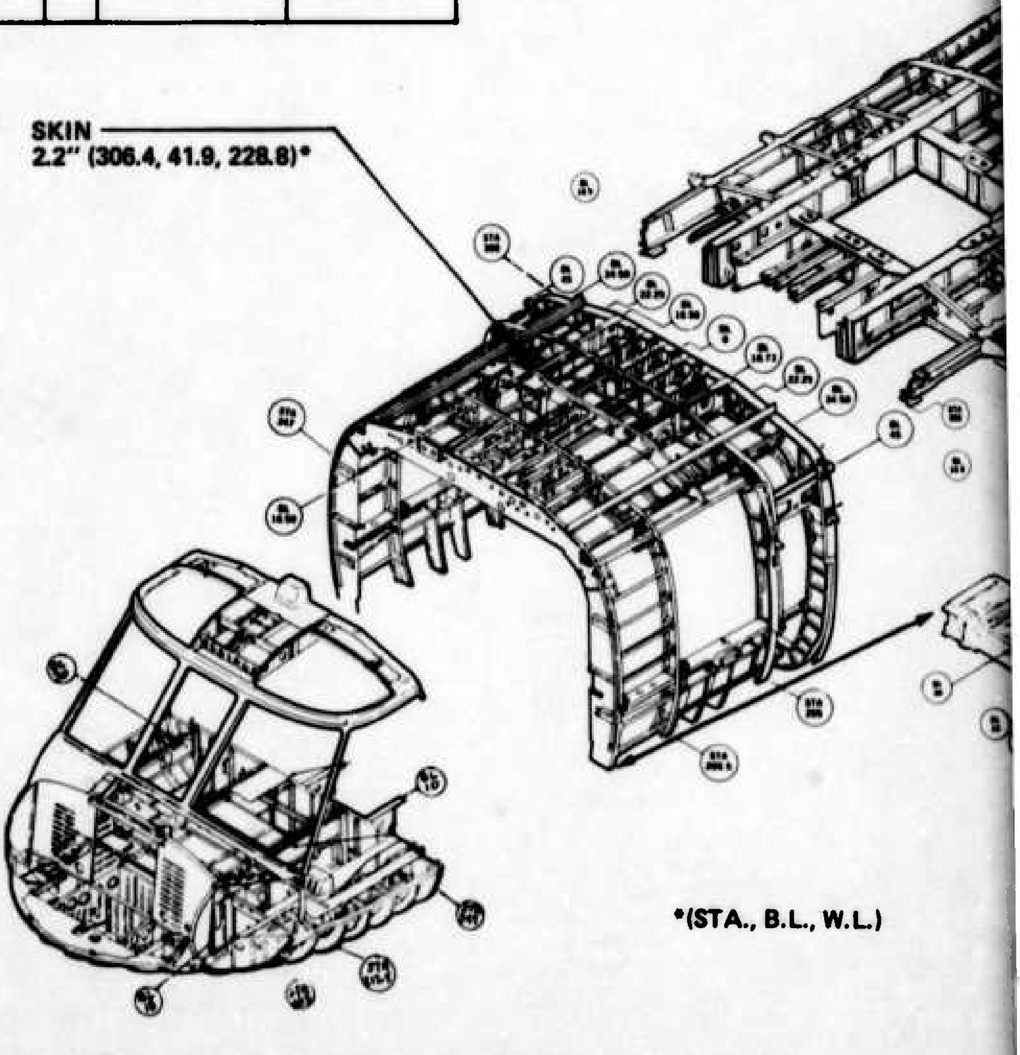
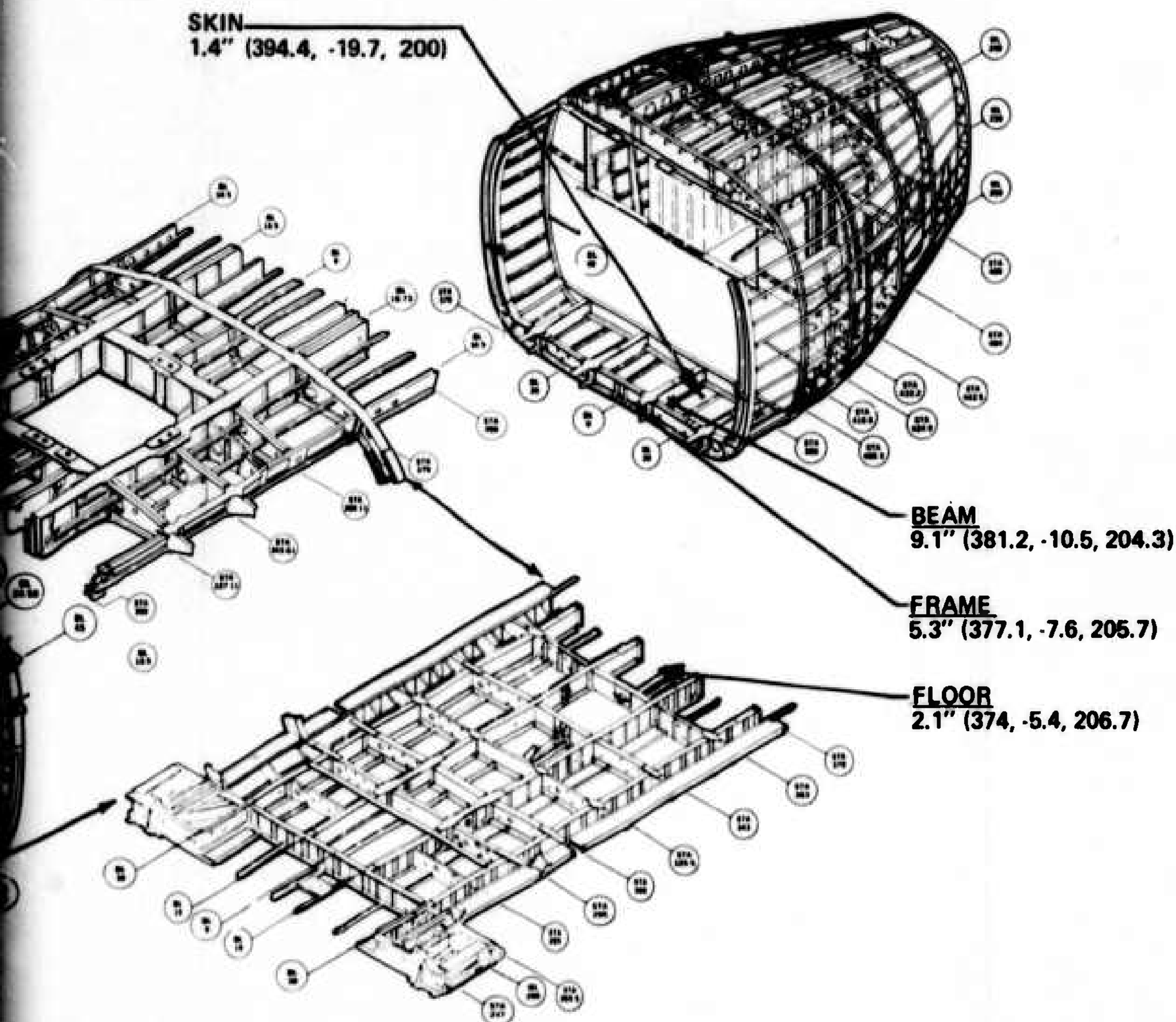


Figure 27. Sample API Damage Description for the Forward Sections of the Airframe


SKIN
1.4" (394.4, -19.7, 200)
BEAM
9.1" (381.2, -10.5, 204.3)
FRAME
5.3" (377.1, -7.6, 205.7)
FLOOR
2.1" (374, -5.4, 206.7)

W.L.)

BALLISTIC DAMAGE DESCRIPTION

SHEET 1 OF 1

CASE NUMBER			PROJECTILE	STRIKING VELOCITY
44	32	94	API	2961

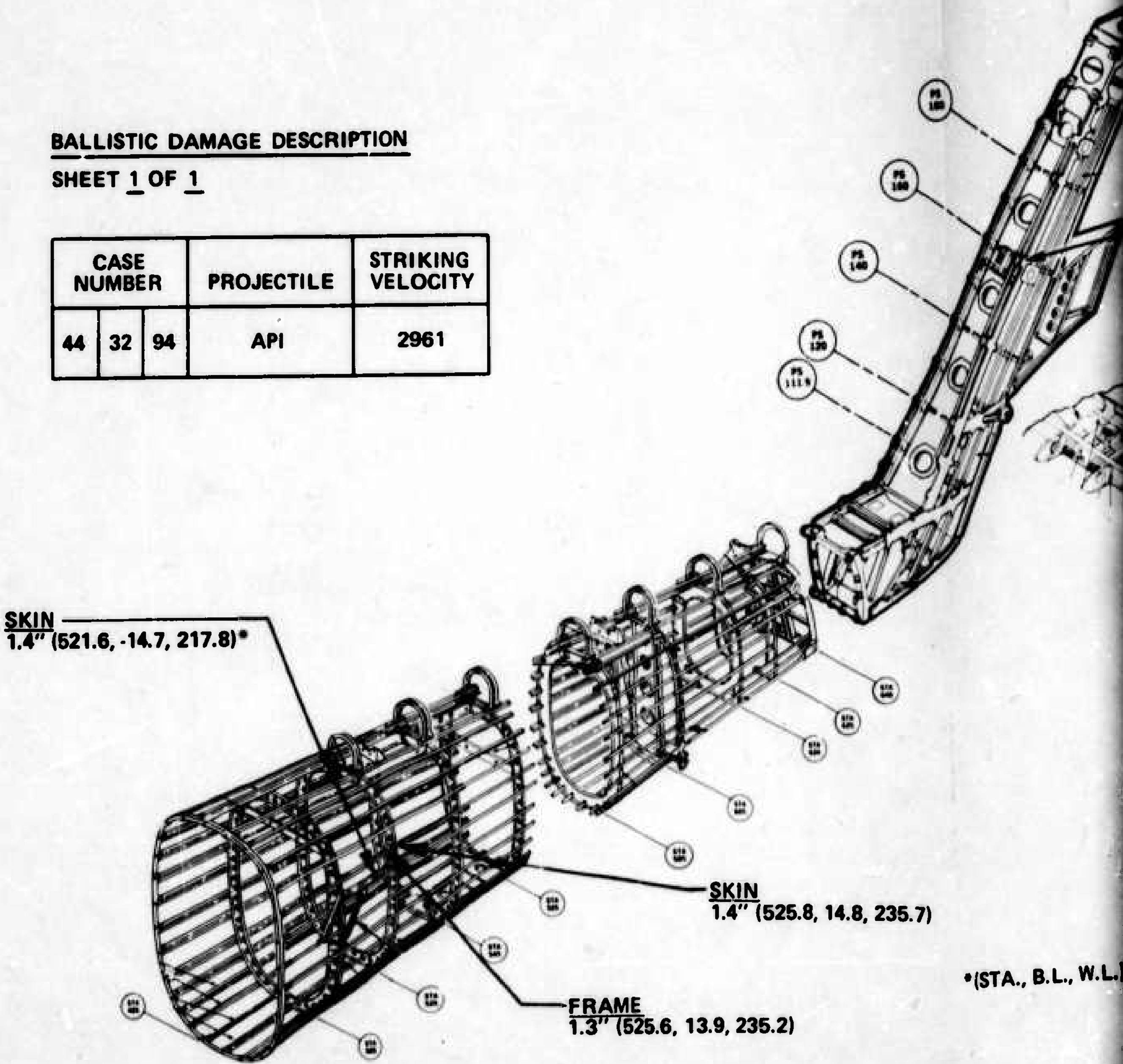
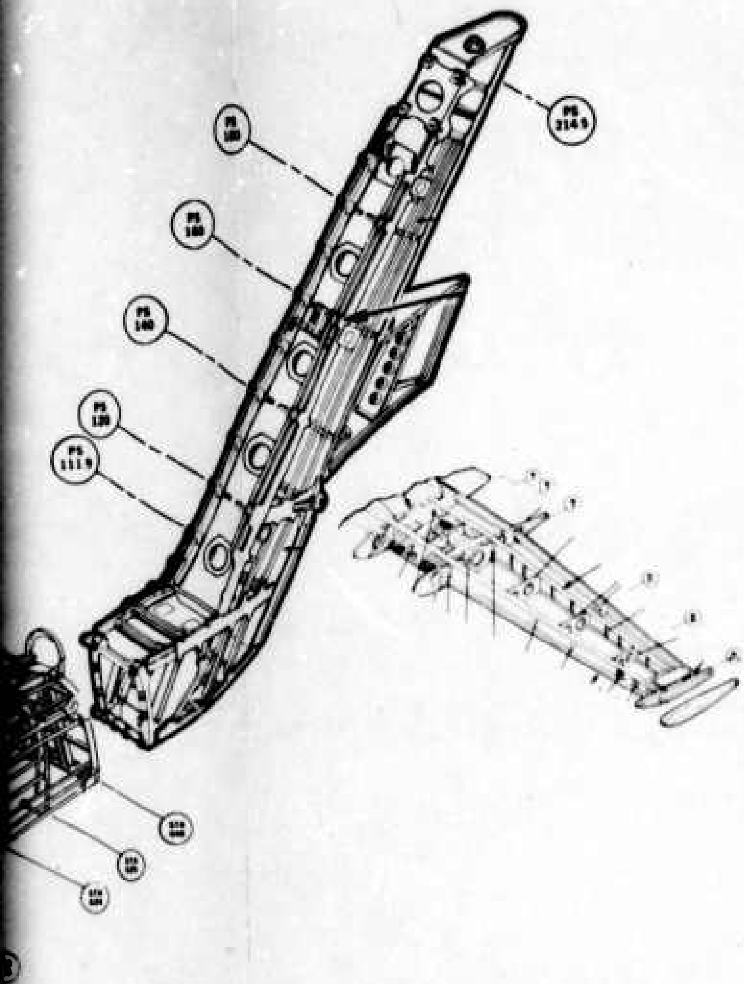


Figure 28. Sample API Damage Description for the Tail Sections of the Airframe



N
(525.8, 14.8, 235.7)

*(STA., B.L., W.L.)

35.2)

2

** PATH OF PROJECTILE THROUGH AIRCRAFT **

CASE NO. 3

STA	WL	BL	STA	WL	BL	STA	WL	BL	STA	WL	BL
561.5	167.3	84.6	451.2	214.2	48.8	341.0	261.0	13.0	230.8	307.8	-22.8
557.0	169.2	83.2	446.8	216.0	47.4	336.6	262.9	11.6	226.4	309.7	-24.2
552.6	171.1	81.8	442.4	217.9	45.9	332.2	264.7	10.1	222.0	311.6	-25.7
548.2	173.0	80.3	438.0	219.8	44.5	327.8	266.6	8.7	217.5	313.4	-27.1
543.8	174.8	78.9	433.6	221.7	43.1	323.4	268.5	7.3	213.1	315.3	-28.5
539.4	176.7	77.5	429.2	223.5	41.7	319.0	270.4	5.8	208.7	317.2	-30.0
535.0	178.6	76.0	424.8	225.4	40.2	314.5	272.2	4.4	204.3	319.1	-31.4
530.6	180.5	74.6	420.4	227.3	38.8	310.1	274.1	3.0	199.9	320.9	-32.8
526.2	182.3	73.2	416.0	229.2	37.4	305.7	276.0	1.5	195.5	322.8	-34.3
521.8	184.2	71.7	411.5	231.0	35.9	301.3	277.9	0.1	191.1	324.7	-35.7
517.4	186.1	70.3	407.1	232.9	34.5	296.9	279.7	-1.3	186.7	326.6	-37.1
513.0	188.0	68.9	402.7	234.8	33.1	292.5	281.6	-2.8	182.3	328.4	-38.6
508.5	189.8	67.4	398.3	236.7	31.6	288.1	283.5	-4.2	177.9	330.3	-40.0
504.1	191.7	66.0	393.9	238.5	30.2	283.7	285.3	-5.6	173.5	332.2	-41.4
499.7	193.6	64.6	389.5	240.4	28.8	279.3	287.2	-7.1	169.0	334.0	-42.9
495.3	195.4	63.1	385.1	242.3	27.3	274.9	289.1	-8.5	164.6	335.9	-44.3
490.9	197.3	61.7	380.7	244.1	25.9	270.5	291.0	-9.9	160.2	337.8	-45.7
486.5	199.2	60.3	376.3	246.0	24.5	266.0	292.8	-11.4	155.8	339.7	-47.2
482.1	201.1	58.8	371.9	247.9	23.0	261.6	294.7	-12.8	151.4	341.5	-48.6
477.7	202.9	57.4	367.5	249.8	21.6	257.2	296.6	-14.2	147.0	343.4	-50.0
473.3	204.8	56.0	363.0	251.6	20.2	252.8	298.5	-15.7	142.6	345.3	-51.5
468.9	206.7	54.5	358.6	253.5	18.7	248.4	300.3	-17.1	138.2	347.2	-52.9
464.5	208.6	53.1	354.2	255.4	17.3	244.0	302.2	-18.5	133.8	349.0	-54.3
460.0	210.4	51.7	349.8	257.3	15.9	239.6	304.1	-19.9	129.4	350.9	-55.8
455.6	212.3	50.2	345.4	259.1	14.4	235.2	306.0	-21.4	125.0	352.8	-57.2

AZIMUTH = 198.0
ELEVATION = -22.0

Figure 29. Sample Output from the Shotpath Computer Program

HEI DAMAGE DESCRIPTIONS

Previously, the variables affecting the amount of damage caused by the impact of API projectiles were enumerated. These included various factors associated with the projectile and the target structure. It was concluded that predicting damage effects in a single API case can involve a very complex analysis.

Many of the variables associated with API projectile damage also apply to the explosive projectiles, since in the case of the delay fuze HEI, the initial impact is that of a solid projectile. Predicting damage caused by the HEI is made even more complex, however, by the mechanisms associated with fragmentation, explosive blast, and overpressure. Computer models are currently being developed to analyze and predict HEI damage. No model was available at the time of this program.

The purpose of estimating HEI effects on the Black Hawk airframe was to obtain a sample of representative damage cases which could be used to assess the potential for damage deferrability and interim repair. A rigorous analysis of the HEI damage mechanisms was considered to be neither necessary nor within the scope of the program. (At best, a rigorous analysis could only be expected to provide approximate answers.) Twenty shotlines were selected from the population of 40 shotlines that had been used to construct the API damage cases. The 20 shotlines were chosen to provide a distribution of hits in the six major sections of the airframe. The following procedure was used to estimate HEI damage: 11 B

1. A nonyawed projectile entry was assumed.

2. It was assumed that the projectile detonates approximately 6 inches after the initial penetration of structure (usually skin).

3. Based on the residual velocity of the projectile after the initial penetration and the static velocity of the main spray fragments, the main spray cone angle and main spray fragment velocity were calculated. It was assumed for high velocity projectiles that the less numerous base and fuze attachment fragments would be focused in narrower cones within the main spray cone.

4. Computer graphics were used to plot the fragment cones in the three principal views of the aircraft (Figure 30).

5. The main spray cones were plotted on planview drawings of the airframe (Figure 31).

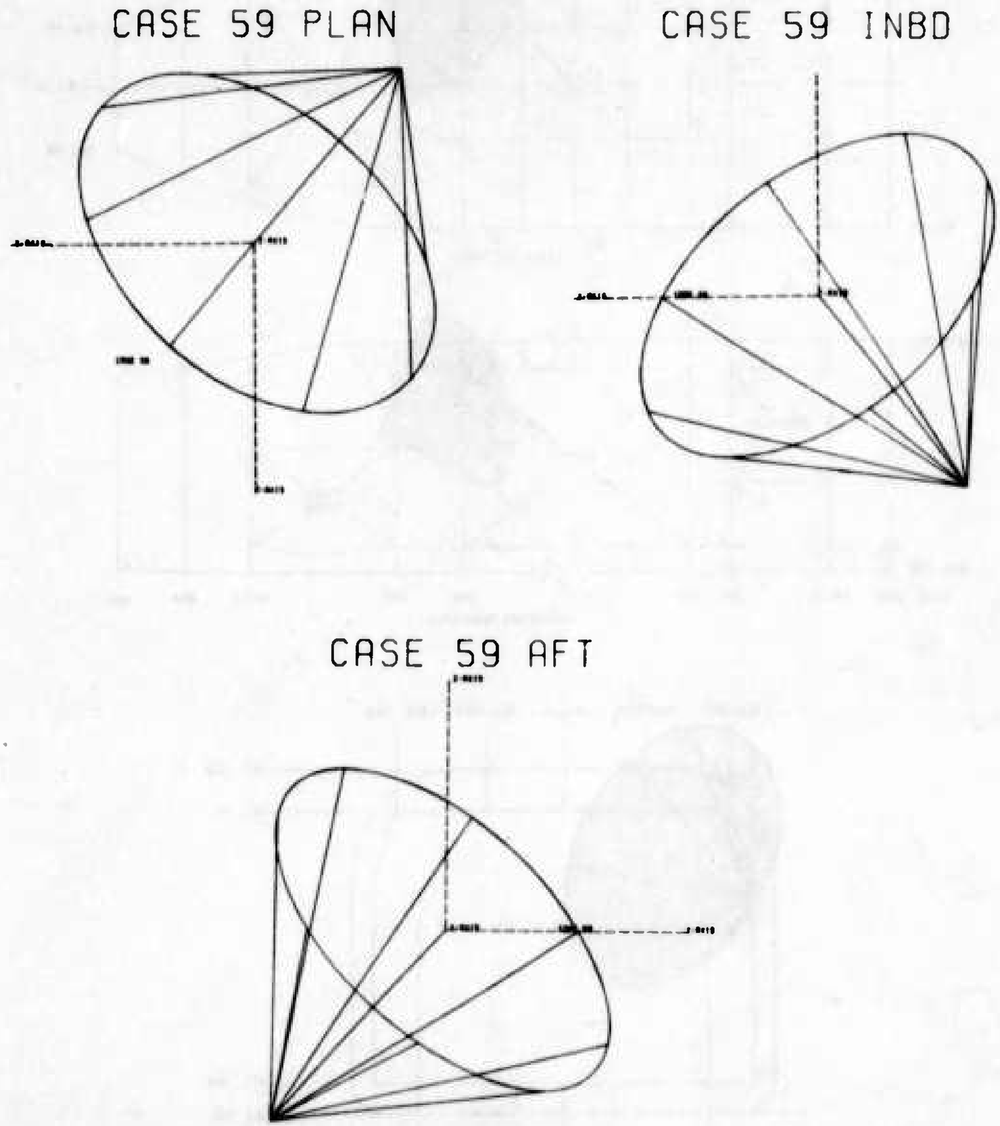


Figure 30. Typical Computer Drawings of Main Spray Fragment Cones Plotted in the Three Principal Views

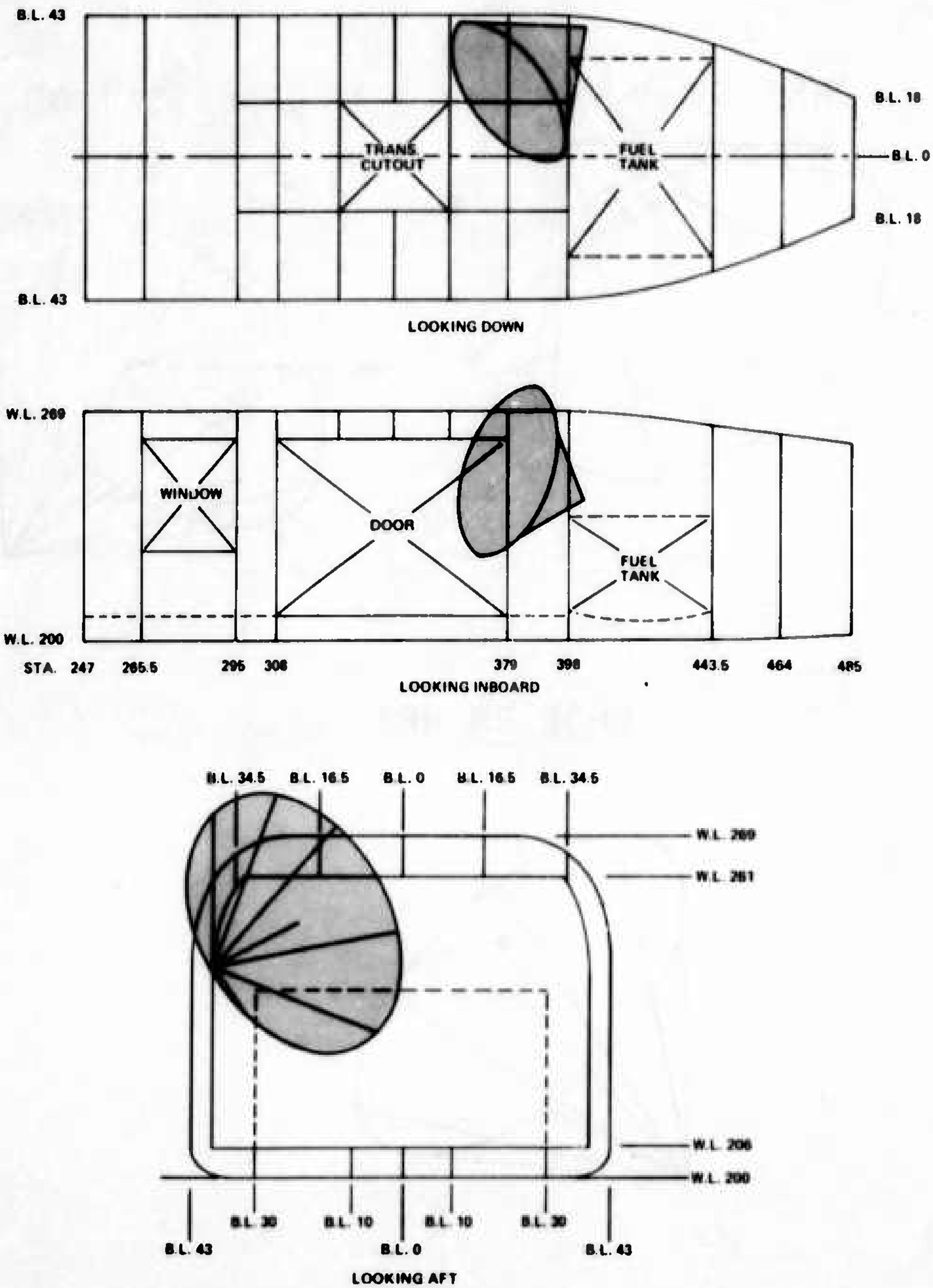


Figure 31. Main Spray Fragment Cones Plotted on Planviews of the Structure

6. The ballistic penetration computer program for fragments was used to develop curves for main spray, base spray, and fuze attachment fragment penetration through aluminum and steel, based on the average mass and shape of the fragments (Figure 32). Curves were developed for fragment density versus cone angle and linear distance from the point of detonation (Figure 33).

7. The fragment penetration curves and fragment density curves were consulted to estimate the depth of penetration through the structure within the described cone. The effects of component masking were considered together with the stress imparted by shock wave and blast.

8. Where the explosion would take place within a confined volume, overpressure damage effects (structural distortion, rupturing, etc.) were estimated.

9. Survivability/vulnerability analysts and airframe stress personnel collaborated to describe the airframe structure damage (elements, areas, degrees of damage). A typical damage description corresponding to the HEI strike illustrated in Figure 31 is given below:

   a. Stringer severed at Sta. 402, W.L. 243, B.L. 45.6.

   b. Two adjacent skin panels ruptured due to blast.

   c. Upper R.H. portion of Sta. 398 bulkhead ruptured due to blast.

   d. W.L. 34.5 beam perforated aft of Sta. 379.

   e. Web of frame at Sta. 379 perforated.

   f. Upper cabin skin perforated between Sta. 360 and Sta. 398, B.L. 0 and B.L. 40.

   g. Frame at Sta. 398 absorbs most of the energy of the fragments.

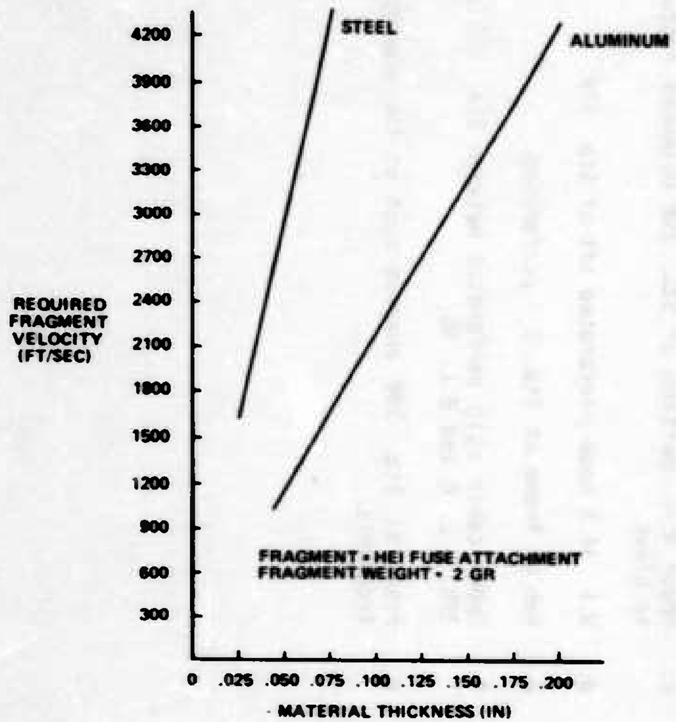


Figure 32. Typical Fragment Penetration Curves

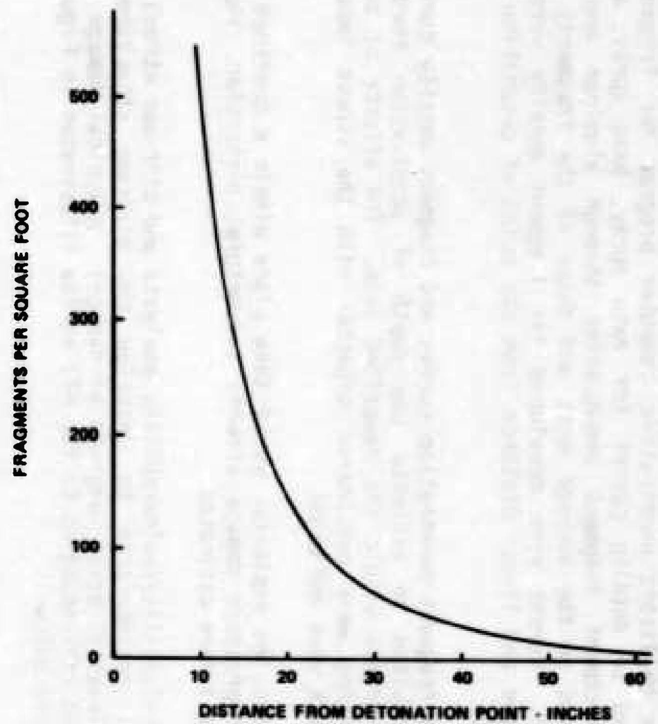


Figure 33. Main Spray Fragment Density vs. Distance From Point of Detonation

STRUCTURAL ANALYSIS OF DAMAGE CASES

API DAMAGE ANALYSIS

Each of the 40 API cases was structurally analyzed to determine if repair of the damage would be deferrable, the operating restrictions that would be required, and the potential for an interim (quick-fix) battlefield repair. Loads criteria, stress reports, and airframe fail-safe testing on the Black Hawk helicopter provided the primary sources of data for the analysis. It was expected initially that it would be necessary to use NASTRAN to evaluate some of the damage cases. It was found, however, that none of the API cases required structural data beyond that already available. (NASTRAN was used for analysis of some of the HEI cases later in the program.) Figure 34 shows the format used to record the results of the structural analysis. The following guidelines were used:

1. It was assumed that the aircraft survived the damage and landed without crashing. Damage to aircraft systems and components other than the airframe was ignored.

2. Each damaged element was analyzed individually and evaluated as though it were the only damage to the airframe. Based on the indicated size of the damage, a judgement was made as to whether the member was partially or totally severed.

3. A judgement was made as to whether the aircraft could be flown with that damage unrepaired (deferred). Three categories of repair deferrability were considered, criteria for which are given in Table 3.

4. For one-time flight deferrability, a judgement was made relative to the operating restrictions (reduced envelope) that would probably be required. Aircraft speed, load factor, and touchdown sink rate were among the factors considered.

5. For the one-time flight and high-risk return to service categories of deferrability, judgements were made relative to the degradation in aircraft attributes that probably would be suffered. This included consideration of dynamic properties and handling qualities, survivability/vulnerability characteristics, and crashworthiness. No actual analysis was done with regard to any of these factors.

6. For the high-risk return to service category of deferrability, a judgement was made relative to the interval at which inspection of the damage would be required. It was assumed that the low-risk deferment would involve conditions not serious enough to require a special inspection.

STRUCTURAL ANALYSIS AND DAMAGE CLASSIFICATION

Case Number		
13	13	30

Projectile
API

Code/Structure	Repair Deferrability				Operating Restrictions			Degradation				Inspection		Repairability			Comments
	None	1-Time Flt.	Ret. to Serv.		Speed	Load Factor	Other (Spec.)	Dynam./Vib.	Perf./Hand.	S/V	Crash-worth.	Ea. Flt.	Other (Hrs)	Interim	Permanent		
			High Risk	Low Risk											Field	Depot	
0077 Skin, Landing Gear Cover				X											X		Nonstructural
0079 Main Frame, Cabin			X		80 kts	1.5g	Sink Speed 8ft/sec			X	X		25	X		X	Partially severed splice angles and straps
7013 Main Frame, Cabin			X		80 kts	1.5g	Sink Speed 8ft/sec			X	X		25	X		X	Partially severed splice angles and straps
7024 Web, Sta. 398 Bulkhead				X											X		
Cumulative Damage		X			80 kts	1.5g	Sink Speed 4ft/sec			X	X						Consider frame totally severed.

Figure 34. Structural Analysis and Damage Classification Worksheet

TABLE 3. REPAIR DEFERRABILITY GUIDELINES

Period of Deferrability	Criteria
None	The damaged structure is incapable of supporting flight and/or landing loads even within a severely restricted operating envelope, or there is a significant probability that even under restricted operation, in the period of a single flight the damage will propagate to a state that causes a catastrophic failure, produces dynamic instability, or otherwise prevents the pilot from maintaining controlled flight of the aircraft.
One-Time Flight	The aircraft is capable of safe, controlled flight, but flying with the damage causes such severe vibration, imposes such severe operating restrictions, and/or so degrades the performance of the aircraft that it cannot effectively perform any of its assigned missions.
Return to Service (High Risk)	The aircraft is capable of performing one or more of its assigned missions with no significant operating restrictions, but flying with the damage so degrades the survivability characteristics of the aircraft that destruction of the aircraft would almost certainly occur if the airframe were damaged again in combat, and/or flying with the damage so degrades the crashworthiness of the airframe that the crew would almost certainly be lost in a crash.
Return to Service (Low Risk)	The aircraft is capable of performing one or more of its assigned missions with no significant operating restrictions and with no significant degradation of performance, combat survivability, or crashworthiness, and there is a negligible probability that in the period between inspections the damage will propagate to a significantly more serious state.

7. Next, a judgement was made as to whether the damaged element could possibly be repaired with a quick-fix or interim repair. A repair of this type was considered to be one that would either allow a one-time flight of the aircraft for evacuation purposes or would allow the aircraft to return to service for a limited number of missions. If it was judged that damage could be simply repaired with conventional methods or that only a permanent repair would be effective, the interim repair block was not checked.

8. Finally, for each damaged element a judgement was made as to whether permanent repair of the damage would be accomplished in the field or at depot. Permanent repair was defined as one which would allow the aircraft to return to service indefinitely with no operating restrictions.

9. After all damaged elements had been analyzed individually, an assessment was made of the deferrability of the total (cumulative) damage to all structural elements, including the operating restrictions and/or degraded performance that would be involved.

HEI DAMAGE ANALYSIS

The 20 HEI damage cases were grouped by area of the airframe and by similarity of damage. This was done to cover, where possible, two or more cases with a single structural analysis.

It was agreed with the Army that returning the aircraft to service with deferred combat damage would require that the structure be able to withstand full limit loads. The first step of the analysis evaluated the damaged structure's ability to meet this requirement. Stress reports and fail-safe testing on the Black Hawk helicopter airframe provided the primary source of data for the analysis. In several cases, the available data was not sufficient to analyze the damage condition and it was necessary to use NASTRAN and the Black Hawk finite element analysis model to calculate the residual strength of the structure with the damaged elements removed (Figure 35) . If it was determined that the structure would be able to withstand limit loads, the damage was classified as either a low-risk or high-risk deferment based on the criteria described earlier for the API damage analysis. Judgements were made relative to any degradation in attributes that would be suffered as a result of flying with the damage unrepaired and of frequency at which inspection would be required. The capability of performing an interim or permanent repair in the field was also assessed. The analysis was recorded in the format shown earlier in Figure 34.

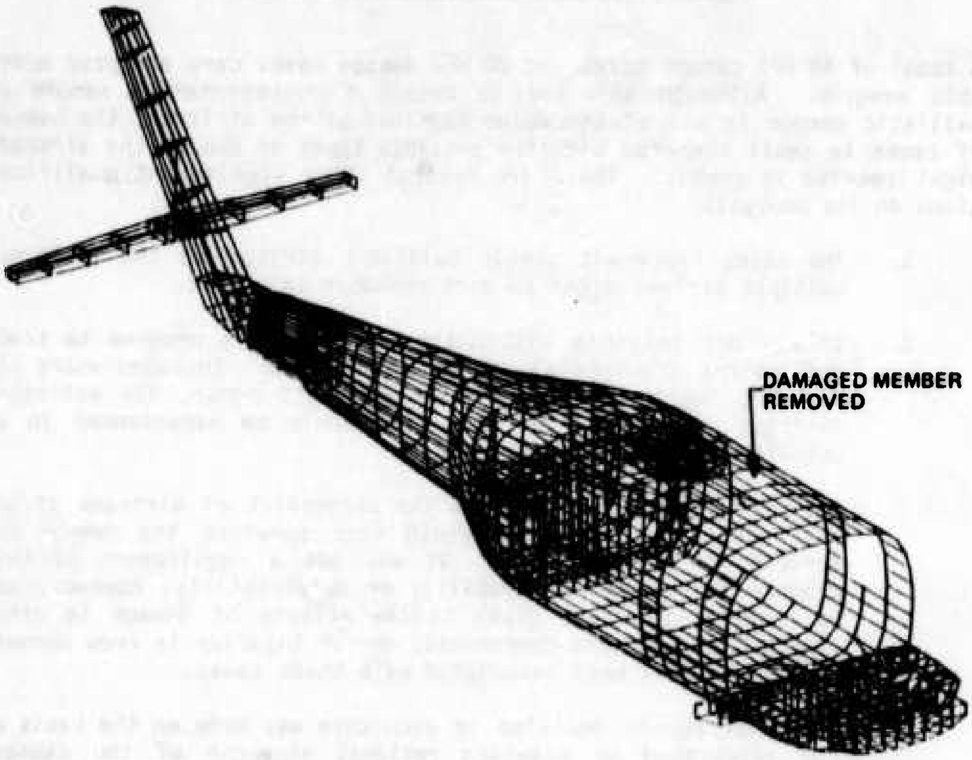


Figure 35. The UH-60A Finite Element Model Modified to Reflect Load Paths Removed by Combat Damage

For those cases where it was determined that the damaged structure would be unable to carry limit loads, an analysis was made to determine if the damaged structure would be able to safely complete a one-time flight under a reduced operating envelope. It was agreed with the Army that the criteria for allowing a one-time flight would include the ability to withstand a minimum load factor of 1.5 g. (Although it is possible to fly the aircraft and not exceed a smaller load factor, e.g., 1.2 g, it was felt that the structure should be able to withstand unanticipated gust and maneuver loads.) A speed of 80 knots was generally specified for the one-time flight, this being the speed at which the minimum power is required and at which vibratory stresses are lowest. Other operating restrictions, degraded performance, and inspection requirements were assessed as previously covered under the API damage analysis.

RESULTS OF THE COMBAT DAMAGE ANALYSIS

A total of 40 API damage cases and 20 HEI damage cases were analyzed under this program. Although selected to obtain a representative sample of ballistic damage in all of the major sections of the airframe, the number of cases is small compared with the possible types of damage the aircraft might receive in combat. There are several other significant qualifications on the analysis:

1. The cases represent single ballistic strikes on the airframe; multiple strikes might be more probable in combat.

2. It was not possible within the scope of this program to trace deflections (ricochets) of API projectiles. In cases where the modeling indicated that a ricochet would occur, the estimated airframe damage may be less than would be experienced in an actual encounter.

3. Analysis indicates that from the standpoint of airframe structure alone, the aircraft would have survived the damage described in all 60 cases. It was not a requirement of this program to assess vulnerability or survivability, however, and no consideration was given to the effects of damage to other aircraft systems and components, nor of injuries to crew members that might have been associated with these cases.

4. The defer/repair decision in each case was made on the basis of the calculated or assessed residual strength of the damaged structure. Possible adverse effects of the damage on dynamic properties were noted, but it was not possible to analyze these effects. It is possible that some of the cases could involve dynamic instability, severe aircraft vibration, or handling qualities problems that would preclude deferring repair.

5. The judgement that an aircraft would be allowed to return to service with damage unrepaired required that the damaged airframe be able to carry full limit loads. This is a conservative criterion, since an aircraft would probably experience limit loads very rarely in combat, particularly in slow NOE flight. Less stringent criteria would have allowed a greater percentage of the damage cases to be classified as deferrable for return to service.

6. Cases were selected for analysis to provide a sample of damage in each of the six major areas of the airframe. The distribution by areas of the airframe is therefore not representative of the distribution that would actually occur in combat.

For all of the above reasons, the analysis conducted under this program provides only a general indication of the potential for deferring repair of airframe combat damage.

RESULTS OF THE API DAMAGE ANALYSIS

The 40 selected shotlines were analyzed to the point of identifying the structural members penetrated by the projectile. Analysis of the resulting damage in a sample of cases disclosed that differences between the small caliber and large caliber API threats were not significant enough from a structural standpoint to warrant separate treatment. With the Army's concurrence, it was decided to complete the structural analysis with only the larger threat.

Table 4 compares the calculated number of structural impacts and penetrations of airframe structure for the sample of 40 cases. Overall, it was estimated that approximately 20% more airframe structure was impacted or penetrated by the large API traveling along the same shotlines as the small API. This does not reflect accurately the relative penetration capability of the two projectiles against airframe structure, however. In many cases it was calculated that both projectiles would be stopped by the same mass (aircraft component) or would be deflected at the same point via impact with a surface at a high angle of obliquity.

TABLE 4. AIRFRAME STRUCTURE IMPACTS AND PENETRATIONS FROM THE API THREAT MODELING

	Impacts/Penetrations			
	Small API		Large API	
Airframe Area	Skin	Framing	Skin	Framing
Cockpit Lower Structure	7	16	8	16
Cabin Upper Structure	7	11	9	17
Cabin Sides	2	1	2	1
Cabin Lower Structure	5	7	5	10
Rear Fuselage Lower Structure	2	3	2	5
Rear Fuselage Sides	3	3	4	4
Rear Fuselage Lower Structure	7	12	7	15
Tailcone	5	3	5	3
Pylon	3	4	4	5
Stabilator	4	2	5	2
Total	45	62	51	78

Figure 36 summarizes the results of the damage deferrability analysis for the API threat. As shown, all of the damage was classified as deferrable, the great majority at low risk. Less than 10% of the damage to individual members was classified as high risk. (To emphasize the definition made earlier in the report, under both risk classifications the aircraft is fully mission capable and able to enter combat with no operating restrictions; the risk relates to the adverse effect on the aircraft's survivability and/or crashworthiness if additional airframe damage is suffered.) A high level of deferrability is evident also for the cumulative damage in the 40 cases, 75% of it classified as low risk. Only 10% of the cumulative damage cases were judged to be limited to a restricted flight envelope. Among the sections of the airframe, damage to the cabin sides resulted in the lowest level of deferrability. The result is based on only three strikes in this area, however, two of which were judged to penetrate the cabin main frames.

Judgements relative to a possible degradation of attributes associated with the simulated API strikes indicated that vibration and handling qualities might be adversely affected by API damage to the tail rotor pylon and stabilator. There were six cases involving this type of damage. There were a larger number of cases where the simulated API damage was judged to have a potentially degrading effect on S/V and crashworthiness, nine cases for which S/V was judged to be degraded, and ten cases for which crashworthiness was judged to be degraded. All of these cases involved damage to either the cockpit lower structure, the cabin, or the rear fuselage.

RESULTS OF THE HEI DAMAGE ANALYSIS

Twenty cases of simulated HEI damage were analyzed. Based on the estimated airframe damage alone, it was determined that repair would be deferrable in all 20 cases. For nine of the cases (45% of the total), it was judged that repair could be deferred for a one-time flight of the aircraft under a restricted (80 kn, 1.5 g) operating envelope. Four cases (20% of the total) were judged to be deferrable for unrestricted flight under the high-risk classification and seven cases (35% of the total) for unrestricted flight under the low-risk classification. Results of the damage deferrability analysis are shown in Figure 37.

The 20 HEI damage cases included one or more simulated strikes in each of the six major sections of the airframe, including the tail pylon and stabilator. The number of cases analyzed is small, however, and it is therefore difficult to draw positive conclusions. It appears from the cases studied that the majority of HEI-caused airframe damage (single hit) will be deferrable at least for a one-time flight of the aircraft. If the criteria for return to service were made less stringent than the requirement to sustain full limit loads, many of the one-time flight deferments probably could be moved into the high-risk return to service classification.

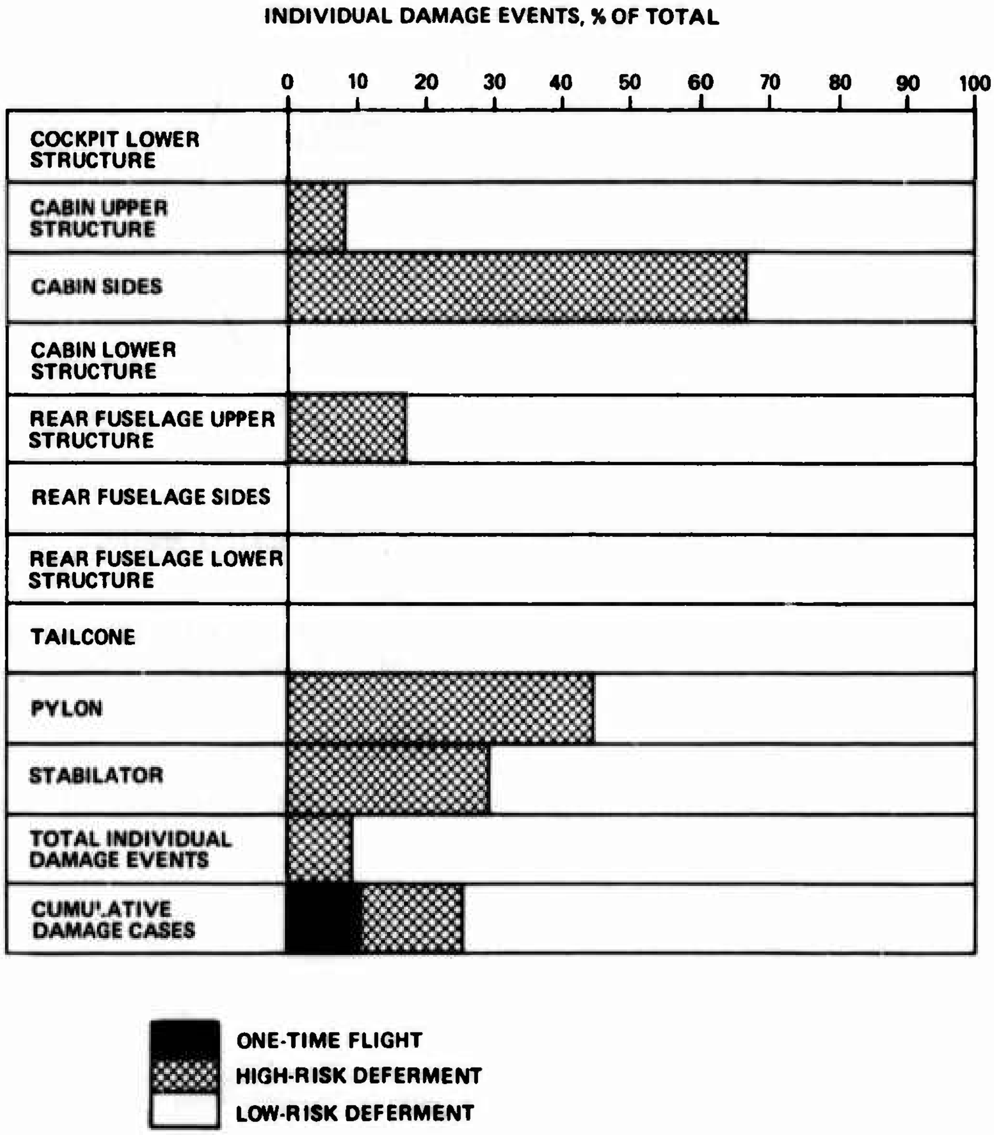


Figure 36. Summary of the API Damage Deferrability Analysis

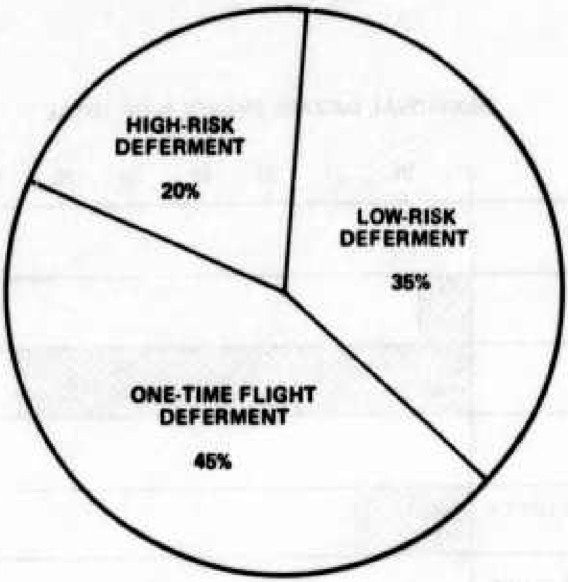


Figure 37. Summary of the HEI Damage Deferrability Analysis

The estimated degradations of attributes associated with the one-time flight and high-risk deferments of HEI damage are summarized below:

	Number of Cases	
Degraded Attribute	One-Time Flight	High-Risk Deferment
Vibration	6	3
Handling Qualities	6	
S/V	5	3
Crashworthiness	5	2

As previously stated in connection with the API damage cases, the estimated degradation in attributes associated with deferring repair of the described damage was a judgement on the part of the analyst. No actual analysis of damage effects was made. It will be noted that degradation in the form of increased vibration was anticipated for the damage associated with three of the high-risk deferments. If this judgement is correct and the vibration levels were severe, this factor might be cause for restricting deferment to a one-time flight. Consistent with the definition of a high-risk deferment, all four of these cases also involved a predicted degradation in S/V characteristics and/or crashworthiness.

COMBAT DAMAGE ASSESSMENT TECHNIQUE

Inspection and assessment of airframe combat damage in the field can be a complex undertaking. Unlike other components of the helicopter, whose condition can be quickly assessed by inspection and whose replacement is comparatively simple, the airframe is made up of a complex network of interdependent and redundant elements. Because of variations in load environment, design margins, and structural redundancy, similar damage to similar appearing elements in different parts of the airframe can have significantly different effects on airworthiness. And since most primary structure is integral with the airframe, it is not always practical to replace damaged elements when doubt exists about their structural integrity.

Considerable information is required by the inspector, either directly or in interpreted form, to enable him to assess airframe combat damage and determine the risks involved in deferring repair:

1. The load environment and margins of safety in the damaged area

2. The types of structural elements involved (longerons, beam caps, stringers, etc.)

3. The modes and extent of damage to specific structural elements and the relative criticality of damage location

4. The significance of the cumulative damage to all structural elements

5. The amount of structural redundancy remaining

6. The possibility of producing dynamic instability if the aircraft is flown with the damage

7. The potential degradation in performance, handling qualities, survivability and crashworthiness

8. The likelihood of damage propagation if the aircraft is continued in service, the effects on the aircraft if propagation to complete failure occurs during flight, and the intervals of inspection required.

The inspector cannot be expected to evaluate all of these factors, nor does he need to if the relevant conditions can be anticipated beforehand, an engineering analysis is made of the pertinent variables, and the results reduced to simple criteria for his use.

The combat damage criteria provided to personnel in the field must be simple and nonambiguous, consisting mainly of graphical presentations.

70

Complex structures drawings and engineering data will not be appropriate for the combat environment. The inspector must be able to examine the damaged aircraft, make some simple calculations, and decide on the proper course of action. He must be sure that the condition he is referencing in the repair handbook is the same as the one he observes on the aircraft.

The ability to defer repair of airframe combat damage will depend upon the residual strength and stiffness of the damaged structure. There must be confidence that the damaged structure can withstand continued loading and that the damage will have no unacceptable effects on aircraft performance, vibration, and handling qualities. From the standpoint of strength, the factors to be considered include:

1. The number and type of structural members that are damaged
2. The extent and location of the damage
3. The ability of the damaged members to carry load
4. The proximity of the failed members and the redistribution of loads into the surrounding structure
5. The margins that exist in the redundant load paths at the critical design condition and/or at some reduced load factor.

TECHNICAL APPROACH

Several approaches to establishing combat damage assessment criteria for the field were investigated. The selected approach is based on the development of failure criticality numbers that reflect the degree of structural degradation that would be caused by the failure of individual members or combinations of members in specific areas (zones) of the airframe. The numbering scheme reflects both the criticality of the individual failures and their structural interaction, considering the relative spacing and distribution of the affected members. For purposes of illustration, the development and application of the concept are described with respect to one major section of structure, the helicopter tailcone.

Although the tailcone is a relatively simple structure, it may be among the more complex sections of the airframe from the standpoint of damage assessment. This is because there are many possible combinations of damage that could effect approximately the same degree of structural degradation. In other areas of the airframe where loads are carried by a few principal members, assessing damage will be comparatively more straightforward.

Stringers, frames, and skin panels are the principal elements of the tailcone. The stringers carry the tailcone bending loads. The frames provide column stability to the stringers and overall stability to the structure. The skin panels carry torsion moments and shear loads.

Development and Presentation of Failure Criteria

The first step in developing combat damage assessment criteria is to establish limits on damage to individual members. To simplify the assessment task, under the proposed approach the inspector is given a set of criteria which enables him to decide whether a member is failed or not failed. He does not concern himself with intermediate degrees of damage.

Failure criteria are based on the type of member, the load environment, and the design margin. In general, the threshold is set at the degree of damage which would render the member incapable of supporting ultimate loads. This may seem conservative for combat damage; however, since the criteria establish a simple failure threshold (a go/no-go limit), it is possible to have many damaged but nonfailed members in the structure. When these are combined with failed members, structural integrity may be more seriously degraded than would be indicated by the failed members alone. Since damage below the failure threshold is effectively being ignored, some measure of conservatism is necessary.

As an example, in the case of the stringers in the tailcone, two modes of failure are considered: a local failure that would cause crippling under an axial load and a failure extending over several inches in length that would reduce the stringer's inertia or bending stiffness with a resultant loss of column stability. A preliminary analysis indicates that damage of up to 15% of the section could be tolerated before reaching either failure condition. It might be found after detailed analysis that higher failure thresholds could be tolerated for some stringers in some areas of the tailcone. It is felt that unless very substantial increases in tolerable damage could be shown, variations in failure criteria for different areas of a structure would not be worth the complexity they would add to the assessment procedure. It is preferable to work with averages or nominal values in order to keep the assessment simple.

Presentation of failure criteria in the maintenance handbook should be as graphical as possible. Complex tables and lengthy written instructions should be avoided. Where exceptions to general criteria exist, they should be omitted from the handbook unless the benefit of incorporating them is very substantial. Exceptions add complexity and may lead to confusion and errors. It is better to accept small penalties on the side of conservatism than to invite errors in such a crucial undertaking.

Figures 38 and 39 show a proposed presentation of failure criteria for the skin panels in the tailcone. The criteria were developed without benefit of a detailed analysis and are intended for illustration only. In each case, the limits on damage at the failure threshold are given first. This is the amount of damage that can be tolerated without classifying the member as failed. Next, simple sketches are used to illustrate conditions which would cause the member to be judged failed. Using diagrams of this type, the inspector examines all of the combat-damaged members in the tailcone and classifies each as failed or nonfailed.

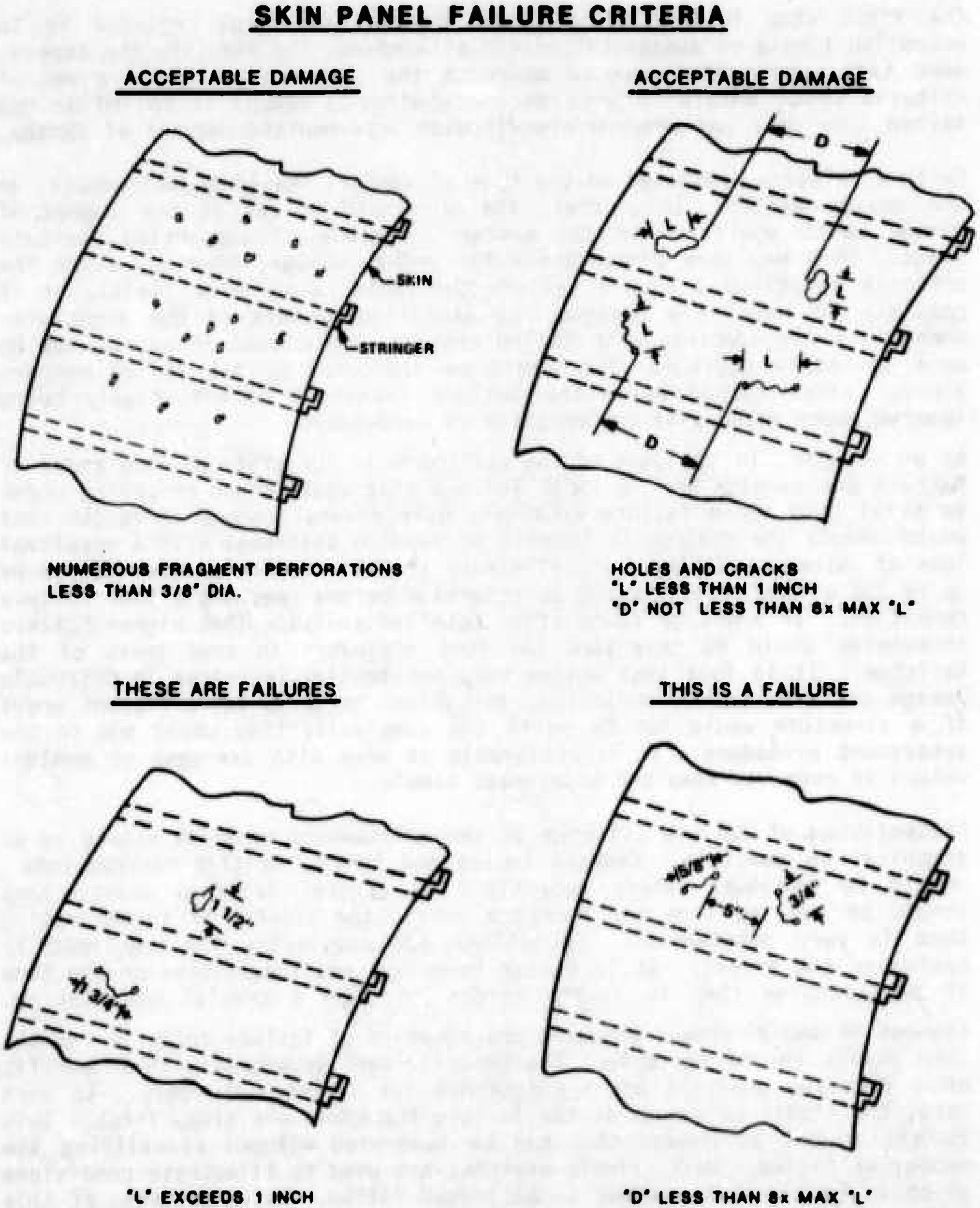
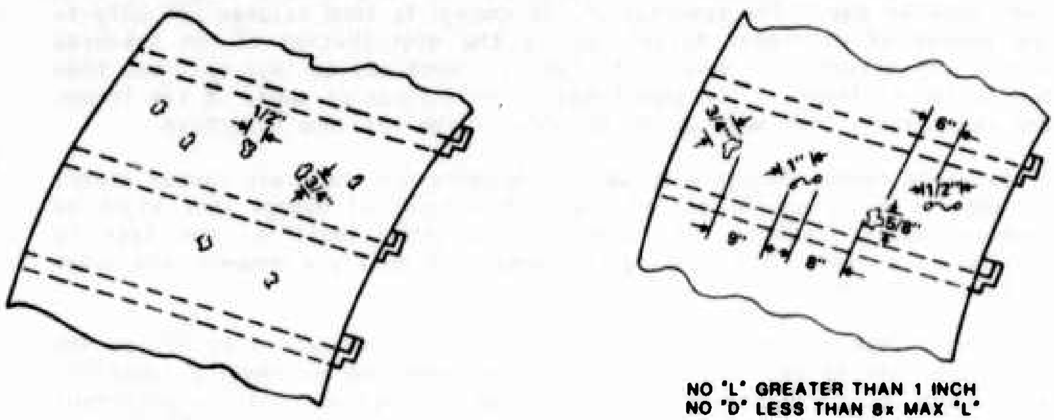


Figure 38. Typical Failure Criteria (1 of 2)

SKIN PANEL FAILURE CRITERIA
(CONTINUED)

THIS MAY BE A FAILURE | **THIS IS NOT A FAILURE**



NO "L" GREATER THAN 1 INCH
NO "D" LESS THAN 8x MAX "L"

FRAGMENT PERFORATIONS
EXCEED 3/8" DIA.

Figure 39. Typical Failure Criteria (2 of 2)

14
F

Development of Damage Assessment Criteria

Combat damage will rarely be confined to a single structural member. More often, it will involve multiple members and multiple zones of the airframe. Multiple failures of the same member in different zones are also possible. Pursuing the tailcone illustration, and considering first the stringers alone, combat damage could involve many combinations of failures and failure locations. The factors influencing the severity of the damage are listed below.

Factor	Severity of Damage: Minor	Severity of Damage: Major
Number of Stringers Failed	One	Multiple
Number of Failures Per Stringer	One	Multiple
Stringer Proximity	Separated	Adjacent
Distribution of Failures (Zones)	Multiple	One
Zone Proximity	Separated	Adjacent

Obviously, the least severe damage is a single failure of a single stringer. Somewhat more severe is the failure of two or three stringers that are widely separated by zones (bays) and locations within zones. Most severe would be the failure of several or more adjacent stringers in the same zone or bay. The severity of the damage is thus related not only to the number of stringers failed but to the distribution of the failures within the structure. Several failed stringers may be less critical than two failed stringers. The same types of relationships apply to the frames and skin panels that make up the balance of the tailcone structure.

A realistic combat damage assessment procedure for the field cannot expect to address individually all of the combinations of damage that might be experienced in combat. The proposed approach simplifies the task by developing a system for scoring the damage to multiple members and zones of the structure.

The first task in developing the damage scoring scheme is to divide the structure into zones. The zones should be separated via readily identifiable items of structure (frames, stringers, longerons, etc.), preferably without reference to fuselage Stations, Waterlines, and Butt Lines, and preferably without the need for measurements on the part of the inspector. Zones should be sized in a manner that facilitates the development and specification of the damage scoring point system. A convenient zone size would be one that places the maximum amount of damage to any one type of member in a zone at the upper limit of the high-risk or one-time flight point range, as subsequent discussion will cover.

Figure 40 shows a tentative zoning of the tailcone. Each zone contains one frame, three stringers, and three skin panels. In the case of the Black Hawk helicopter tailcone on which the illustration is based, a different zoning scheme would probably be used for the aftmost section of the tailcone where fewer structural members carry the loads and where the spacing of members is significantly more concentrated. Under the proposed scheme, the airframe can be divided into any logical number of sections for purposes of zoning.

<u>Development of Damage Scoring Point Systems</u>

The key element of the proposed approach is the development of a point system which is used to score the severity of combat damage to a structure, based on the individual members that are failed, the total number of members that are failed, and their relative proximity. Points are based on the specific loading conditions which design each area of the structure and on the contribution of individual members to the integrity of the structure at these design conditions. NASTRAN is used when required to evaluate the redistribution of loads within the structure with individual members and combinations of members removed and to assess the reduced margins that would exist in the surrounding members.

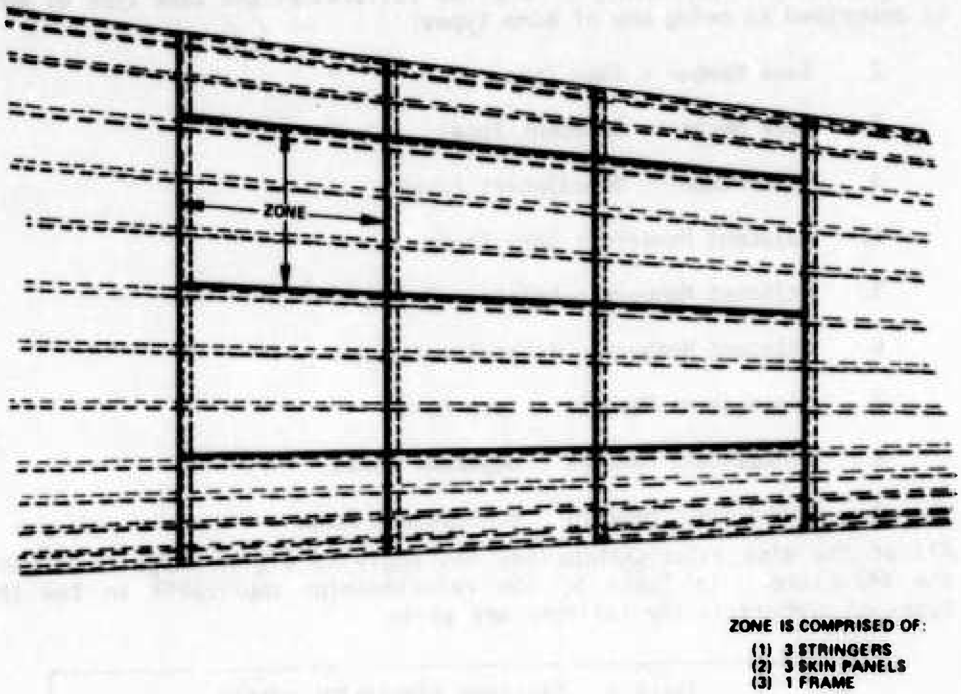


Figure 40. Tailcone Zoning Concept

Points are established in a manner that reflects the interaction of damage to multiple zones of the structure. Obviously, if the zones containing damage are in widely separated parts of the aircraft, they can be assessed independently. Within a given section of the airframe, the tailcone for example, zones containing damage that are separated by two or more bays might also be assessed independently. As the distance between damage zones narrows, the probability of structural interaction increases. Damage to immediately adjacent zones usually represents the worst case and may in fact be a continuation or enlargement of the same damage.

The point system reflects these relationships by weighting the failures in the structure both by their individual severity and by their degree of interaction. Failures of members in widely separated areas of the structure result in a much lower damage score than the same set of failures concentrated in one area of the structure. Point systems are developed for each type of member (frame, stringer, etc.) in the structure. These are later combined to derive an overall damage score for the structure.

The proximity relationship of any two failures of the same type of member is described as being one of nine types:

1. Same Member - Same Zone
2. Same Member - Adjacent Zones
3. Same Member - Nonadjacent Zones
4. Adjacent Members - Same Zone
5. Adjacent Members - Adjacent Zones
6. Adjacent Members - Nonadjacent Zones
7. Nonadjacent Members - Same Zone
8. Nonadjacent Members - Adjacent Zones
9. Nonadjacent Members - Nonadjacent Zones

All of the nine relationships may not apply to a given type of member in the structure. In Table 5, the relationships applicable to the three types of members in the tailcone are shown.

TABLE 5. TAILCONE STRUCTURAL MEMBER PROXIMITY RELATIONSHIPS

	Stringers	Skin Panels	Frames
Same Member			
Same Zone	X	X	X
Adjacent Zones	X	X	X
Nonadjacent Zones	X	X	X
Adjacent Members			
Same Zone	X	X	
Ajacent Zones	X	X	X
Nonadjacent Zones	X	X	X
Nonadjacent Members			
Same Zone	X	X	
Adjacent Zones	X	X	
Nonadjacent Zones	X	X	X

Under the proposed concept, the combat damage repair handbook would contain simple illustrations of the possible proximity relationships for a given area of the structure. Figure 41 is a sample set of illustrations for the stringers in the tailcone. The proximity relationships will probably be similar for stringers in all of the other areas of the airframe, and it is expected that with a little experience, it will be unnecessary for the inspector to refer to these diagrams in the repair handbook.

In the engineering analysis that develops the point scores for a given type of member, the possible combinations of failures of that member in a single zone are listed in order of increasing severity. As mentioned previously, zones should be so defined that the final point system places the maximum damage to any one type of member in any one zone at the upper point limit for one category of deferrability. In the case of the tailcone example, zones were established such that the maximum damage to any one of the three types of members would be at the upper limit of a high-risk deferment.

As the first step of the scoring point development, points are assigned to each of the possible failure proximity relationships for the member. A tentative set of points for the tailcone stringers is shown in Table 6. Where the damage involves multiple stringers, the term "primary failure" refers to the one failure the inspector selects as the starting point for scoring the damage. This is explained further in the following section.

Initially, the points are assigned to simply reflect the relative severity of failure proximity on a minimum to maximum scale. This is done by assigning a point value of 0 or 1 to the least severe condition (a second failure of the same stringer in the same zone) and increasingly larger point values to increasingly more severe conditions. For the tailcone illustration, the most severe condition is represented by a failure of an adjacent stringer in the same zone or an adjacent zone.

In the next step of point system development, the point values are refined to reflect the relative severity of the possible combinations of damage to each type of member in the structure. This need only be carried to the degree of damage that would exceed the limits for a one-time restricted flight of the aircraft. For example, if the limit on the number of adjacent stringers that can be failed is four, it is unnecessary to consider combinations of adjacent stringer failures greater than four.

Table 7 gives a listing of possible combinations of stringer failures in two vertically adjacent zones in the tailcone (total of six stringers). The list is ordered by increasing structural severity. The initial scoring point values from Table 6 were assigned to each failure combination, and the damage scores were examined for consistency with the relative degree of structural damage represented by each combination of failures. The point values were then used to score a variety of assumed damage conditions involving combinations of adjacent and nonadjacent stringer failures in adjacent and nonadjacent zones.

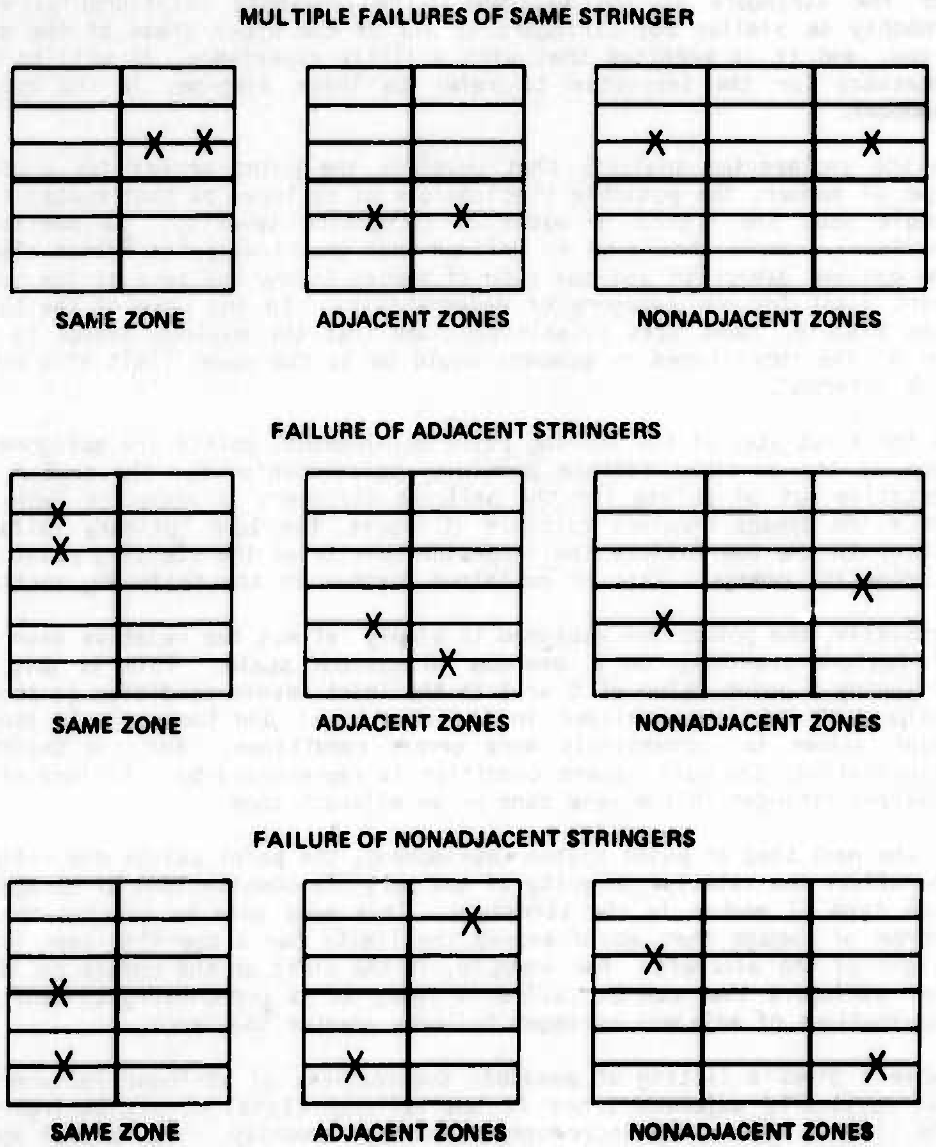


Figure 41. Example Proximity Relationship Diagram

TABLE 6. STRINGER DAMAGE POINT SCORES

	Points
Primary Failure	5
Same Stringer - Same Zone	0
Same Stringer - Adjacent Zones	1
Same Stringer - Nonadjacent Zones	1
Adjacent Stringer - Same Zone	5
Adjacent Stringer - Adjacent Zones	5
Adjacent Stringer - Nonadjacent Zones	4
Nonadjacent Stringer - Same Zone	4
Nonadjacent Stringer - Adjacent Zones	4
Nonadjacent Stringer - Nonadjacent Zones	3

TABLE 7. STRINGER FAILURE COMBINATIONS FOR TWO VERTICALLY ADJACENT ZONES ORDERED BY RELATIVE DAMAGE SEVERITY

No. of Failures	Proximity	Initial Score	Adjusted Score	Deferrability Limit
1		5	6	
2	Same Stringer	5	6	
2	Nonadjacent	9	11	
				←----- Limit of Low Risk
2	Adjacent	10	12	
3	Nonadjacent	13	16	
3	Adjacent	15	18	
				←----- Limit of High Risk
4	Adjacent	20	24	
				←----- Limit of One-Time Flight
5	Adjacent	25	30	

It was found that the intial point values did not adequately differentiate degrees of damage. In some cases it was possible to arrive at approximately the same total score for two different combinations of damage when structural analysis revealed they were not of the same severity. Increasing the point values by 1 achieved the desired discrimination. The rightmost column of Table 7 lists the scores for stringer damage in vertically adjacent zones of the tailcone, based on the adjusted point values.

The final point system enables the user to assess any combination of failed members in a structure (stringers in this case) and obtain a score that will place the damage in the proper category of repair deferrability. The same type of analysis is carried out to develop damage scoring point systems for the other members in the structure. For the tailcone, this would include the skin panels and frames. In the final step of this phase of the analysis, damage conditions involving combinations of different types of members (stringers and skin panels for example) are scored and compared with the degree of structural degradation shown by analysis. Scores are compared with point limits for the categories of repair deferrability to verify that damage involving combinations of failed members is properly assessed. Further refinement of the point systems may be necessary to achieve this result.

At this stage, the damage assessment technique allows the user to count the failures of various members in a structure, assign points to each failure based on its location and proximity to other failures, and sum the points to obtain an overall scoring of the damage. Scores can be compared with established thresholds to determine if repair is deferrable within one of three categories.

There may be cases where failure of multiple members in a structure are partially redundant, and to score them with full point values would overestimate the damage. In the case of the tailcone, failure of a frame and an adjacent stringer is essentially redundant, since the frame failure acts to destabilize the adjacent stringers. Actual failure (severing) of the stringer in that area does not make the structural condition significantly worse. In order not to overstate damage, redundant failures must be anticipated and provisions made in the assessment procedure to modify (reduce) damage scores where they occur.

Under this program, the proposed concept was applied in preliminary form to the development of damage assessment criteria for a portion of the tailcone structure. It was found that several iterations produced a set of point values that produced reasonable damage scores for a variety of assumed damage conditions and that the indicated decisions to defer or not defer repair based on the scoring could be supported by structural analysis. The form of the preliminary assessment scheme is shown in Figure 42. The procedure that the inspector would be directed to follow is described next.

TAILCONE DAMAGE SCORING

STEP 1. RECORD FAILURE COUNTS.

IMPORTANT: VERIFY THAT ALL DAMAGE HAS BEEN INSPECTED AND THAT ALL FAILED MEMBERS HAVE BEEN COUNTED. RECORD FAILURES.

STRINGERS (TABLE X-X)	SKIN PANELS (TABLE X-X)	FRAMES (TABLE X-X)
A	B	C

REDUNDANT FAILURES (STRINGER FAILURE ADJACENT TO FRAME FAILURE)

D

STEP 2. SCORE STRINGER FAILURES.

STRINGERS		FAILURES	PTS.	TOT. PTS.
PRIMARY FAILURE (1 ONLY)		1	x 6	
SAME STRINGER (SEE FIG X-X)	SAME ZONE		x 0	
	ADJACENT ZONE		x 2	
	NONADJACENT ZONE		x 2	
ADJACENT STRINGERS (SEE FIG X-X)	SAME ZONE		x 6	
	ADJACENT ZONES		x 6	
	NONADJACENT ZONES		x 5	
NONADJACENT STRINGERS (SEE FIG X-X)	SAME ZONE		x 5	
	ADJACENT ZONES		x 5	
	NONADJACENT ZONES		x 4	
	TOTALS			

STEP 3. COMPARE TOTALS. BLOCK E

IMPORTANT: TOTAL FAILURES MUST AGREE WITH BLOCK A.

STEP 4. SCORE SKIN PANEL FAILURES.

SKIN PANELS		FAILURES	PTS.	TOT. PTS.
PRIMARY FAILURE (1 ONLY)		1	x 6	
SAME SKIN PANEL (SEE FIG X-X)	SAME ZONE		x 0	
	ADJACENT ZONES		x 6	
	NONADJACENT ZONES		x 4	
ADJACENT SKIN PANELS (SEE FIG X-X)	SAME ZONE		x 6	
	ADJACENT ZONES		x 6	
	NONADJACENT ZONES		x 5	
NONADJACENT SKIN PANELS (SEE FIG X-X)	SAME ZONE		x 5	
	ADJACENT ZONES		x 5	
	NONADJACENT ZONES		x 4	
	TOTALS			

STEP 5. COMPARE TOTALS. BLOCK F

IMPORTANT: TOTAL FAILURES MUST AGREE WITH BLOCK B.

STEP 6. SCORE FRAME FAILURES.

FRAMES		FAILURES	PTS.	TOT. PTS.
PRIMARY FAILURE (1 ONLY)		1	x 10	
SAME FRAME (SEE FIG X-X)	SAME ZONE		x 10	
	ADJACENT ZONES		x 20	
	NONADJACENT ZONES		x 20	
ADJACENT FRAMES (SEE FIG X-X)	ADJACENT ZONES		x 10	
	NONADJACENT ZONES		x 10	
NONADJACENT FRAMES (SEE FIG X-X)	NONADJACENT ZONES		x 10	
	TOTALS			

STEP 7. COMPARE TOTALS. BLOCK G

IMPORTANT: TOTAL FAILURES MUST AGREE WITH BLOCK C.

STEP 8. SCO

REDUNDA
STRINGE ADJACENT TO

STEP 9. COM

IMPORTANT: T AGREE WITH B

STEP 10. SUM

BLOCK E + BLO F

BLOCK I − BLO H

IMPORTANT: C CALCULATIONS

STEP 11. CH

MAX IN (STRINGE
MAX IN (SKIN PAN
MAX IN (FRAME
MAX IN (TOTAL

WARNING: D DAMAGE SCO ALL BLOCKS

Figure 42. Combat Damage Scoring Worksheet

ILURES.

AIL-RES	PTS.	TOT. PTS.
1	x 6	
	x 0	
	x 6	
	x 4	
	x 6	
	x 6	
	x 5	
	x 5	
	x 5	
	x 4	

BLOCK F

MUST

RES.

FAIL-URES	PTS.	TOT. PTS.
1	x 10	
	x 10	
	x 20	
	x 20	
	x 10	
	x 10	
	x 10	

BLOCK G

MUST

STEP 8. SCORE REDUNDANT FAILURES.

REDUNDANT FAILURES	FAIL-URES	PTS.*	TOT. PTS.
STRINGER FAILURE ADJACENT TO FRAME FAILURE			
TOTALS			BLOCK H

STEP 9. COMPARE TOTALS.

IMPORTANT: TOTAL FAILURES MUST AGREE WITH BLOCK D.

*SAME PTS. AS STRINGER SCORE

STEP 10. SUM DAMAGE SCORES.

$\square + \square + \square = \square$ TOTAL DAMAGE SCORE

BLOCK E + BLOCK F + BLOCK G = BLOCK I

$\square - \square = \square$ ADJUSTED DAMAGE SCORE

BLOCK I − BLOCK H = BLOCK J

IMPORTANT: RECHECK ALL ENTRIES AND CALCULATIONS.

STEP 11. CHECK DEFERRABILITY CRITERIA.

	LOW RISK	HIGH RISK	1-TIME FLIGHT
MAX IN BLOCK E (STRINGER DAMAGE)	13	20	26
MAX IN BLOCK F (SKIN PANEL DAMAGE)	13	20	26
MAX IN BLOCK G (FRAME DAMAGE)	13	20	26
MAX IN BLOCK J (TOTAL DAMAGE)	13	25	30

WARNING: DO NOT DEFER REPAIR UNLESS DAMAGE SCORES ARE BELOW LIMIT FOR ALL BLOCKS IN THAT CATEGORY.

COMBAT DAMAGE SCORING IN THE FIELD

The inspector is instructed to carefully inspect the structure and record the location and extent of damage to each structural member. He is instructed to treat each member and each instance of damage to a member as a potential failure to be assessed. If a stringer is damaged in two locations in the same bay, each damage is treated separately.

The inspector is then directed to consult the failure criteria in the maintenance handbook to determine which of the recorded damage events are to be classified as failures. Reference to the handbook will be unnecessary for failures that are obvious, e.g., members that are heavily damaged or completely severed. The total number of failures are recorded for each type of member in the structure. The combat damage repair handbook might contain Mylar diagrams of the structure on which the inspector records failures with a grease pencil. For the tailcone example being followed, the number of stringer, skin panel, and frame failures are entered in Blocks A, B, and C of Figure 42. Damage events determined to be nonfailures are not considered further.

The inspector is instructed to identify the zone containing the maximum damage and to begin his assessment with that zone. When two or more zones are equally damaged, he selects one as the zone of maximum damage. He then proceeds to score the failures of each type of member. For the tailcone illustration, failures of stringers, skin panels, and frames are scored. If there are no failures of a given type of member in the structure, that portion of the scoring is omitted.

The inspector is directed to select one stringer failure as the primary stringer failure. Normally, the primary failure will be located in the zone of maximum damage, and insofar as practicable, be in a central position with respect to other stringer failures. In the case where stringer failures are scattered and none are located within the zone of maximum damage, he picks a failure in the most central location as the primary failure. The primary failure is recorded in the first block of the stringer failure scoring table.

Each of the remaining stringer failures is scored with respect to its proximity to other stringer failures. Starting with stringer failures closest to the primary stringer failure and moving outward, each failure is scored with respect to its worst case (highest point) relationship to surrounding stringer failures. For example, if the stringer failure being scored is a second failure of a stringer in the same zone (point value 0) and also a failure of an adjacent stringer in an adjacent zone (point value 6), that failure would be scored at the highest of the two point values. It is felt that with minimal training, inspectors can be taught to recognize worst-case proximity relationships. If Mylar diagrams of the structure are provided for the inspector to record failures, this task will be facilitated.

When the scoring is completed, the inspector sums the damage points for stringer failures and verifies his assessment. He then proceeds to score failures of the other types of members in the structure (skin panels and frames in the case of the tailcone). The final task of the scoring is to score redundant failures (if applicable). In the case of the tailcone example, a failed stringer located adjacent to a frame failure is considered redundant and the points assigned to that failure are to be deducted. If the damage involves this situation, the inspector records and scores the redundant failure(s).

This completes the damage scoring. In the final two steps of the assessment, the inspector sums the damage counts for all members in the structure and compares the totals with limits on repair deferrability. To defer repair within one of the three categories, the total damage count for each type of member and the adjusted damage count for all members must be within the stated limits.

FEASIBILITY OF THE ASSESSMENT TECHNIQUE

Based on the preliminary analysis conducted under this program, the proposed combat damage assessment concept is considered to be feasible. Further work will be needed to develop and refine the methods. Although possibly requiring an extensive engineering analysis to develop failure criteria and damage scoring point systems for an entire airframe, application of the assessment technique is believed to be within the skills of Army field personnel. Training of inspectors in the use of the technique would be desirable, but it is believed that the procedures might be kept simple enough that an experienced person could apply them based solely on instructions contained in the handbook. In final form, the handbook would be expected to be relatively short and highly illustrated.

Possible approaches to combat damage assessment in the field are discussed in the section of the report entitled "Combat Maintenance Support Concepts."

Requirement for Conservatism

There will be a need to exercise a reasonable degree of conservatism in the development of combat damage assessment criteria and repair deferrability criteria for an aircraft. In the field, damage may be overlooked, particularly when inspections are being made in a combat situation. Errors may occur in determining which of the damaged members are failed and/or in scoring the failures. Finally, field personnel may deliberately exceed deferrability limits in the belief that they have been conservatively established by the manufacturer. To accommodate these various possibilities and assure that undue risks are not taken, some measure of conservatism will be needed in the process of developing criteria for the field.

REPAIR CONCEPT DEVELOPMENT

The ability to devise an interim structural repair is related to three factors: the amount of damage received (strength/stiffness lost), the structural effectiveness of the repair (strength/stiffness restored), and the risk associated with failure of the repair. The first two of these factors are illustrated in Figure 43.

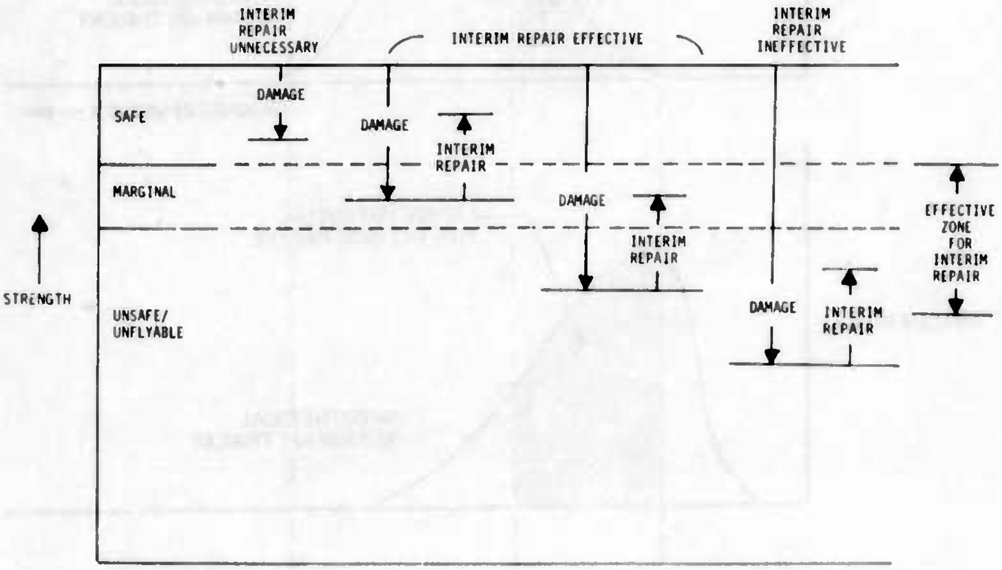


Figure 43. The Potential for Interim Repair Related to Three Key Variables

As shown, there is some level of damage at which the structure is not impaired beyond safe limits, that level being determined by design margins and the degree of structural redundancy present. Damage within these limits requires no repair. There is another level of damage at which structural integrity becomes marginal. At this level the aircraft might be flown unrepaired, with some risk, and also with some restrictions on payload, speed, maneuverability, etc. The third level of damage renders the aircraft unflyable or unsafe to fly, and repair is mandatory. For an interim repair to be effective, it must restore sufficient strength to the structure to elevate it from the marginal category to the safe category or from the unflyable/unsafe category to the marginal or safe categories. The concept is illustrated further in Figure 44.

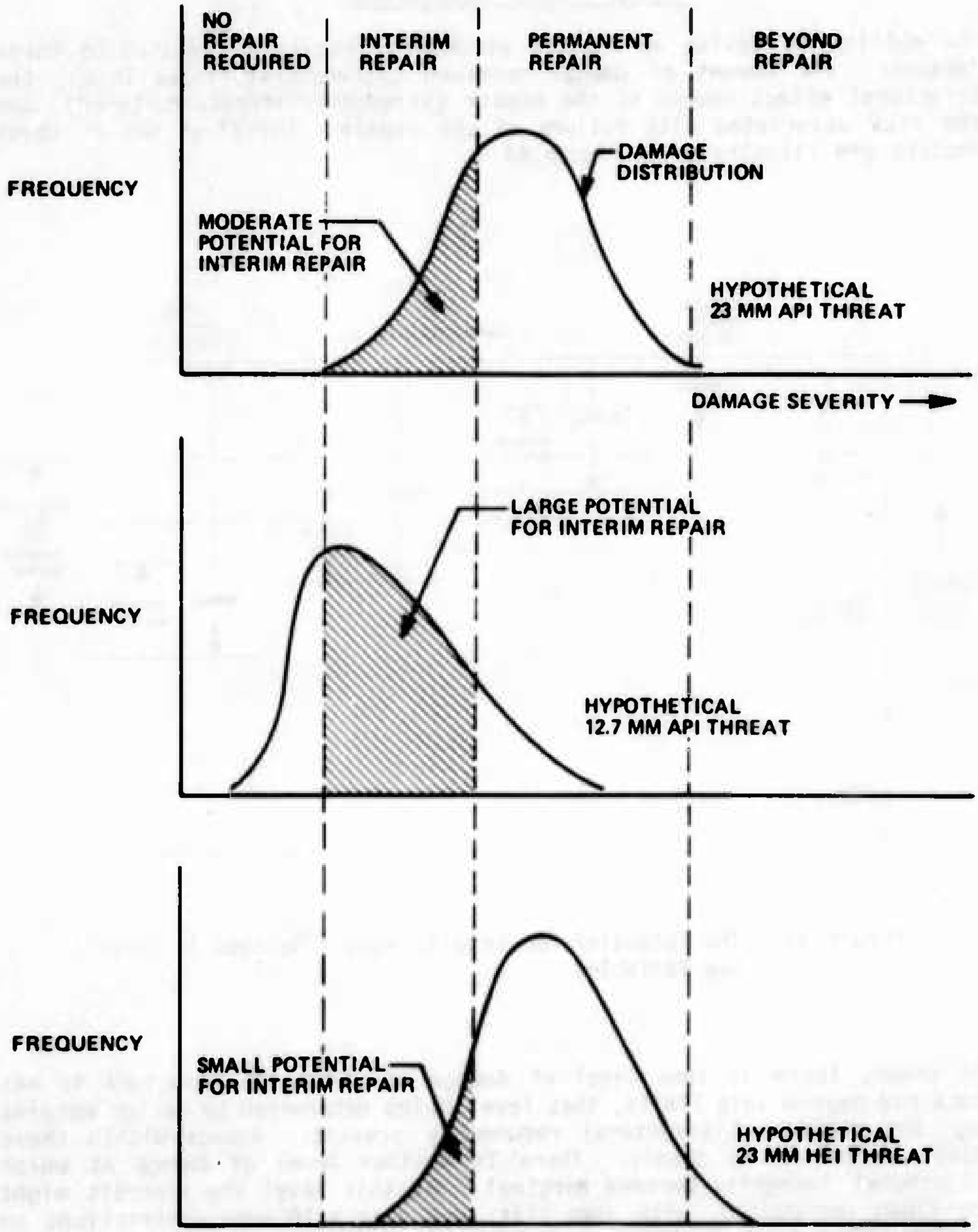


Figure 44. The Potential for Interim Repair Related to the Assumed Threat

The third factor to be considered in the development of interim repairs is the probability of and risks associated with failure of the repair and the consequences of subsequent damage to adjacent structural members. The concept is illustrated in Figure 45. For an undamaged structure, the probability of the applied stresses exceeding the strength of the parts is very small, usually requiring a combination of inherently flawed (low-strength) material and an exceptionally high stress level to produce a failure. The effect of an interim repair that does not fully restore the structure to original strength is to increase the average stresses in the structure, enlarging the region where failure may occur.

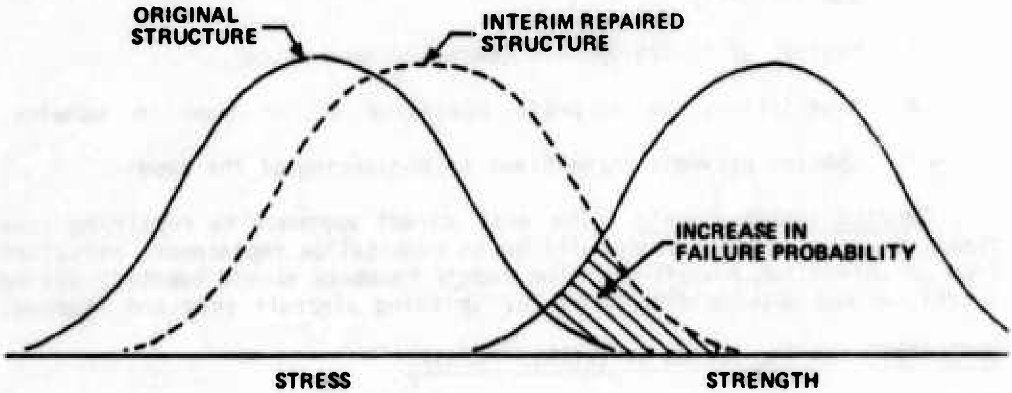


Figure 45. The Effect of Interim Repair on the Probability of Subsequent Failure

COMBAT REPAIR OPTIONS

The options for repair of combat-damaged airframe structure include standard structural repairs, interim or temporary repairs, and cannibalization repairs.

Standard Structural Repairs. Even in the combat environment, there will be situations where airframe damage can be repaired by conventional methods. These would generally include cases where the damage is minor, accessibility is adequate, the standard repair is simple, and there is ample time to make the repair. For the combat environment, conventional repair standards could be relaxed, especially with regard to requirements that are primarily aesthetic.

Interim (Temporary) Repairs. Interim or temporary repairs will be employed in cases where skills, resources, and/or time do not permit a standard repair to be made, and an interim repair will restore sufficient integrity to the structure to allow the aircraft to be flown with an acceptable level of safety. An interim repair is distinguished from a standard repair by one or more of the following characteristics:

1. Less than 100% restoration of structural strength and/or stiffness.

2. Limited durability and/or fatigue life.

3. The creation of alternate load paths (bridging damage) rather than restoration of the original load paths.

4. Addition of substantial weight and/or aerodynamic protrusions to the aircraft.

5. Neglect of finishing work (cosmetic appearance).

6. Restrictions on aircraft operation and/or time in service.

7. Special periodic inspections or monitoring of the repair.

Cannibalization Repair. The most direct approach to repairing some types of major combat damage will be to cannibalize replacement structure from an unrepairable airframe. The repair handbook should identify splice locations and provide directions for splicing aircraft skin and framing.

OBJECTIVES FOR THE DESIGN OF INTERIM REPAIRS

There are basic objectives to be satisfied in the design of interim repairs for combat-damaged airframe structures:

1. Avoidance of internal access via the application of externally applied repairs.

2. Avoidance of hand-forming, fitting, and nesting of parts.

3. Use of shims to avoid joggles when standard shapes are used in lieu of formed parts.

4. Use of repair materials that are compatible with the parent structure (strength, modulus, chemical properties, etc.).

5. Restoration of design ultimate strength; original strength if possible.*

6. Restoration of sufficient structural stiffness to prevent serious vibration problems or critical dynamic instability in the airframe.

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* These were the criteria used for this program. The Army might elect to apply less stringent criteria, e.g., restoration of strength sufficient to carry design limit loads.

7. Ability to verify the structural integrity of the repair immediately after repair and at periodic intervals.

8. No significant deterioration of the repair during the specified operating interval.

9. Sufficient structural redundancy to sustain a minimum acceptable (1.5 g) acceleration after failure of the repair.

10. Skills, tools, and materials that are compatible with the Army combat field environment.

11. Repair in a mean time of 5 hours, maximum time of 24 hours.*

12. Restoration of structural continuity across the damaged area.

13. Avoidance of significant structural eccentricities.

Basic Measures

The minimum requirements for repair of combat damage are a careful inspection and cleanup of the damage, to include removing torn and ragged metal, smoothing holes, and stop-drilling cracks. These basic measures would be prescribed whether a repair is to be made or deferred.

Approach to Combat Damage Repair

Typically, structural repair handbooks do not contain step-by-step procedures for specific repairs to specific components of the airframe. Rather, they contain methods of repairing generic types of structure that can be used throughout the airframe (repair of skin panels, repair of U-channel stiffeners, etc.). In the field, the repairman uses a combination of these detail methods to construct a repair for a given degree of damage to a particular area of the structure.

It is felt that this general approach should be extended to the development of combat damage repairs. Considering the great variety of structures in a typical helicopter airframe and the many possible locations of damage and degrees of damage that might be suffered in combat, there are potentially an enormous number of interim repair schemes that might be devised. Unless the benefits are very significant in terms of reduced skills and repair time, an approach that introduces highly specialized repairs limited to certain types of damage in certain areas of the airframe appears to be generally unattractive.

Versus generic types of repair that are applicable to many areas of the airframe, specialized repairs will tend to increase the volume of data required in the repair handbook. If the repair methods are an extreme departure from the types of repair made in peacetime, airframe repairmen

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* This was an Army-specified objective.

will have acquired no practical experience with them until they enter combat. Learning new techniques under combat conditions will be difficult, and overall performance may be poor, particularly during the crucial early stages of a conflict. Finally, if the specialized repair techniques also involve special materials or tools that are not normally stocked by the supply organization, there is the prospect that they will be unavailable when combat starts.

The approach to combat damage repair adopted in this program is to simplify and ease the tasks of airframe structural repair with the use of techniques, materials, and tools similar to those used in the peacetime field environment. As envisioned, combat repair instructions for the airframe would consist mainly of shortcut methods of repairing generic types of structure wherever they are found in the airframe. The combat repair methods will be similar enough to those he has experienced that the repairman will be able to apply them with little difficulty. As is his practice in peacetime repair of the airframe, the repairman uses a combination of these generic repair methods to construct a repair for combat-damaged structure.

INTERIM REPAIR CONCEPTS

One requirement of this program was to develop interim repair concepts for typical airframe combat damage. Four repair concepts were developed. The concepts cover repair of a variety of primary airframe structure:

1. Typical semi-monocoque skin, frame, stringer construction
2. Partially inaccessible spars in the tail pylon and stabilator
3. Heavily loaded machined fittings in the cabin main framing.

The interim repair concepts are described in the following pages. Although related to specific areas of the Black Hawk helicopter airframe, they describe general approaches to repair that could be used in many other areas of the airframe. Each of the repair concepts is evaluated individually. An overall evaluation of the concepts concludes this section of the report.

To illustrate the concepts simply, the described repairs are confined to localized areas of damage. In cases such as the tailcone, the repairs could be extended to cover much larger areas of damage and multiple framing members. Also, a complete repair is shown in every case. If the urgency of returning an aircraft to service were great, in some cases the decision could be made to install only a portion of the repair, restoring sufficient strength to a structure to bring it within the limits of deferrable damage.

TAIL ROTOR PYLON SPAR INTERIM REPAIR CONCEPT

The tail rotor pylon is a two-spar box beam with corner longerons and intermediate stringers. The front and rear spar webs are stiffened with angle-shaped stiffeners. The front and rear spar caps are back-to-back extruded angles with an internal strap. Reinforced inspection holes are provided in the front spar web along the entire span.

The upper and lower shear decks are built-up sections. A canted bulkhead at the attachment to the tailcone allows the empennage to fold to the right for air transportability. Machined fittings support the intermediate gearbox, tail rotor gearbox, and stabilator. Fairings enclose the leading and trailing edges of the pylon.

The pylon spars are designed to strength requirements and support of pylon shear and bending moments due to tail rotor loads and pylon air loads. Bending moments are supported by tension and compression axial loads in the spar caps. Shear loads are supported by the spar web. The side skins support pylon torsional moments as shear forces in the skin.

Assumed Damage Condition

The tail rotor pylon is a heavily loaded and critical element of the airframe. When primary structural members such as the front and rear spars are involved, only moderate amounts of damage will be amenable to interim repair in the field. Extensive damage will require a standard structural repair or replacement of the pylon.

The pylon is a mechanically assembled sheet metal structure incorporating forged components at highly stressed locations such as the stabilator attachment and pylon fold hinge. Many individual parts are involved in the pylon assembly. Variations in structural details from one area to another largely preclude the development of standardized interim repairs for the pylon, e.g., a repair that can be used without modification in any area of the front spar or rear spar. General approaches to repair can be established, but field personnel will have to improvise to accommodate specific structural details, interferences, etc.

The interim repair concept described herein is based on assumed damage to the front spar of the pylon (Figure 46). With some variation, the repair would be applicable to similar degrees of damage to most areas of both the front and rear spars. The assumed damage comprises the following:

1. A hole in the skin in the immediate area of the damage
2. Missing sections of the back-to-back spar cap angles
3. A missing section of the spar web.

Interim repair concepts are developed for 2 degrees of damage, one in which the section of the missing cap angles is less than 2 inches in length and one in which the missing section is up to 5 inches in length.

Repair Objectives

In addition to the objectives common to all interim repairs (avoiding internal access, minimizing forming of parts, etc.), the following specific objectives apply to the pylon repair:

Cap Angles

1. Restoration of structural continuity across the damaged region.
2. Provision of a section to support both tension and compression axial loads.
3. If repair is external, minimum offset and sufficient section to support the loads as an eccentric column.
4. Sufficient overlap for gradual transition of load.

Web

1. Restoration of structural continuity across the damaged region.

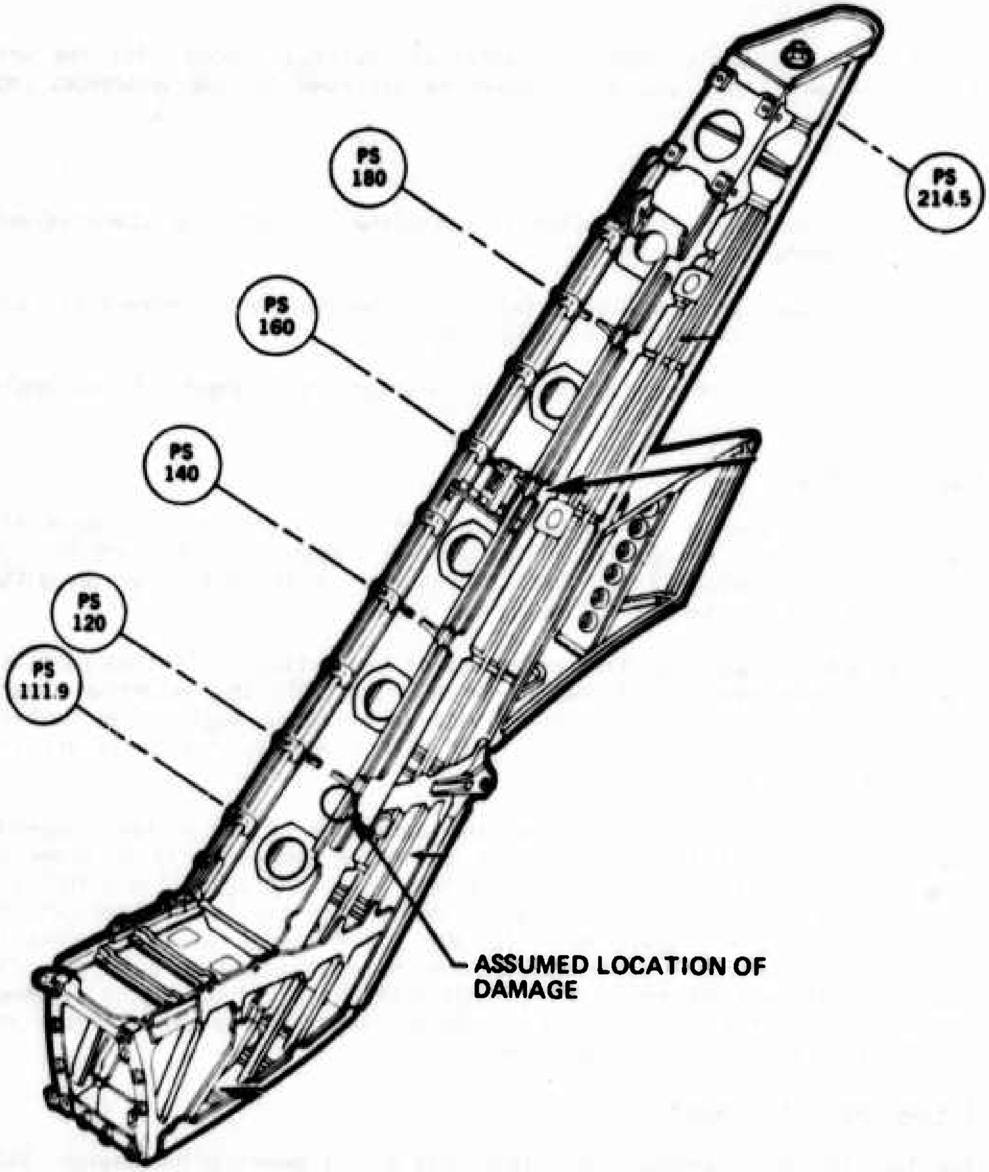

Figure 46. Tail Pylon Spar Interim Repair Concept - Assumed Location of Damage

2. Support of web shear loads; restoration to full strength if possible.

3. If cap angle repair is external, lateral support for the web repair that would otherwise be provided by the undamaged cap angle.

Skin

1. Restoration of structural continuity in both the spanwise and chordwise directions.

2. Support of spanwise axial loads (tension and compression) and support of leading edge fairing loads.

3. Spanwise length of repair equivalent to length of cap angle repair.

Repair Concept

The assumed damage to the pylon front spar is illustrated in Figure 47. The interim repair concept is illustrated in Figures 48, 49, and 50. The entire repair is accomplished from the exterior of the pylon, avoiding the need for access to the blind side of the spar.

The spar web is repaired first using one of two options. If time permits, the web is repaired with a doubler formed from .070-inch aluminum sheet. Alternatively, the web is repaired with an extruded angle, flat doubler, and shim as shown in Figure 48. With either option, the parts are installed with blind rivets.

The cap angle and skin are repaired next using one of two options, depending on the size of the damage. For cap angle damage up to 2 inches in length, a flat strap is cut from .375-inch steel and installed with blind rivets using shims to fill the gap created by the missing sections of the skin and cap angle (Figure 49). For cap angle damage up to 5 inches in length, the flat steel plate is replaced by a skin splice cut from .063 aluminum sheet and external back-to-back extruded aluminum angles as shown in Figure 50. The installation is accomplished with aluminum shims and blind rivets as previously described.

Evaluation of the Repair

The interim repair concept described here will support pylon design loads but does not restore the structure to original strength. Restoration to original strength would require an internal repair and nested parts. This might also be achieved with the external repair by substituting steel for aluminum in the repair parts.

It is estimated that the interim repair of the pylon spar, including making the parts, could be accomplished by two men in approximately 16 hours.

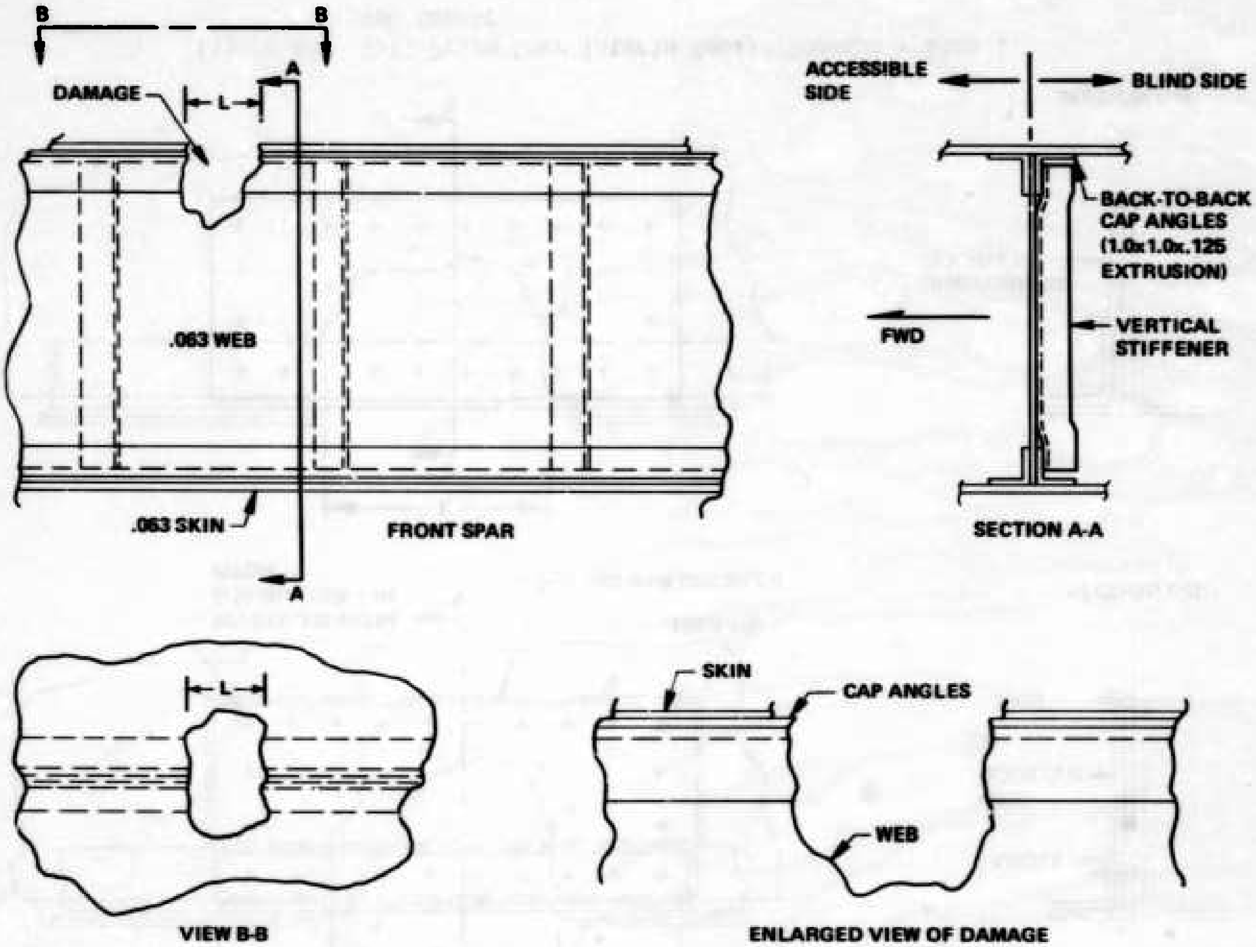

Figure 47. Tail Pylon Spar Interim Repair Concept - Assumed Area and Extent of Damage

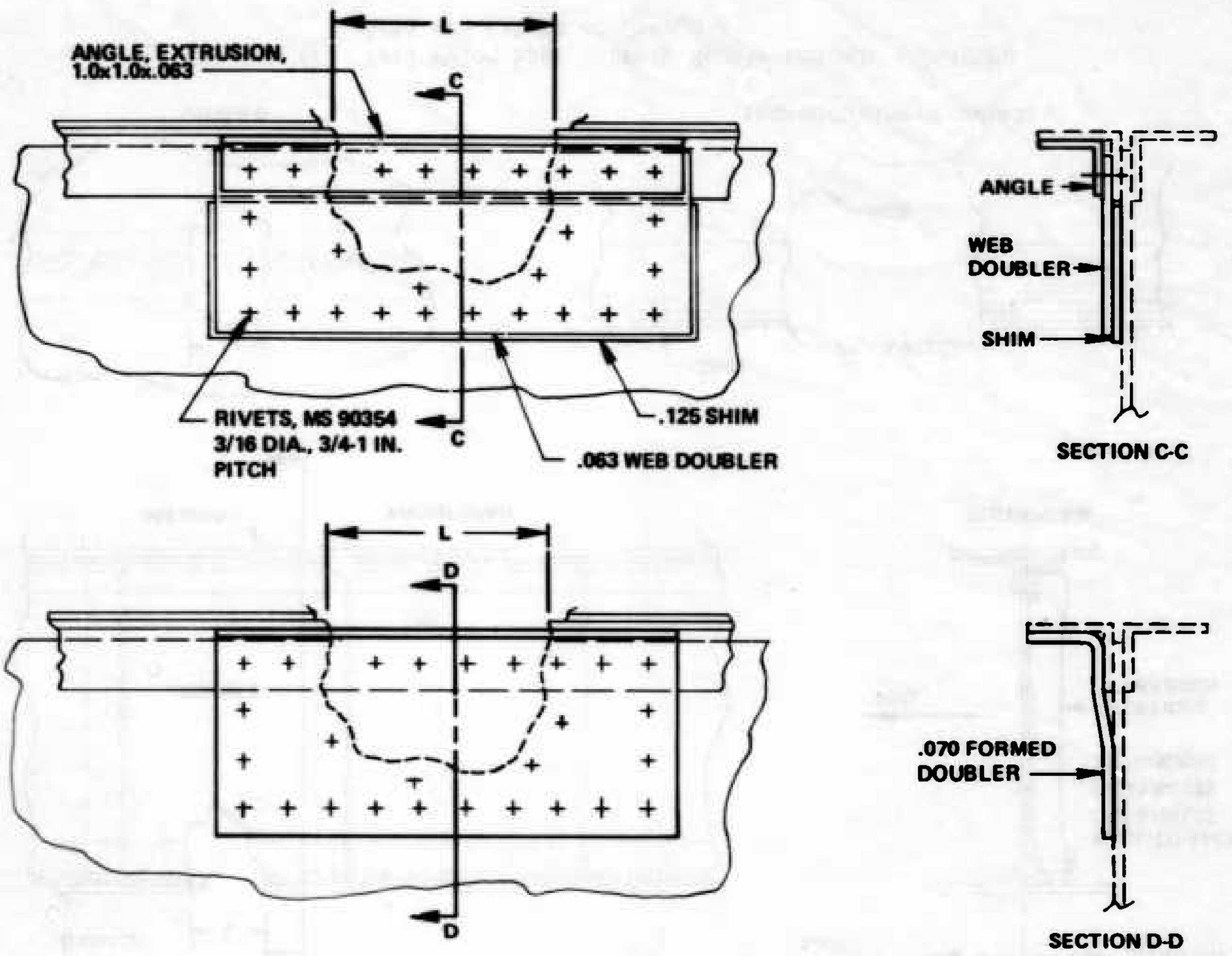

Figure 48. Tail Pylon Spar Interim Repair Concept - Step 1, Web Repair

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B

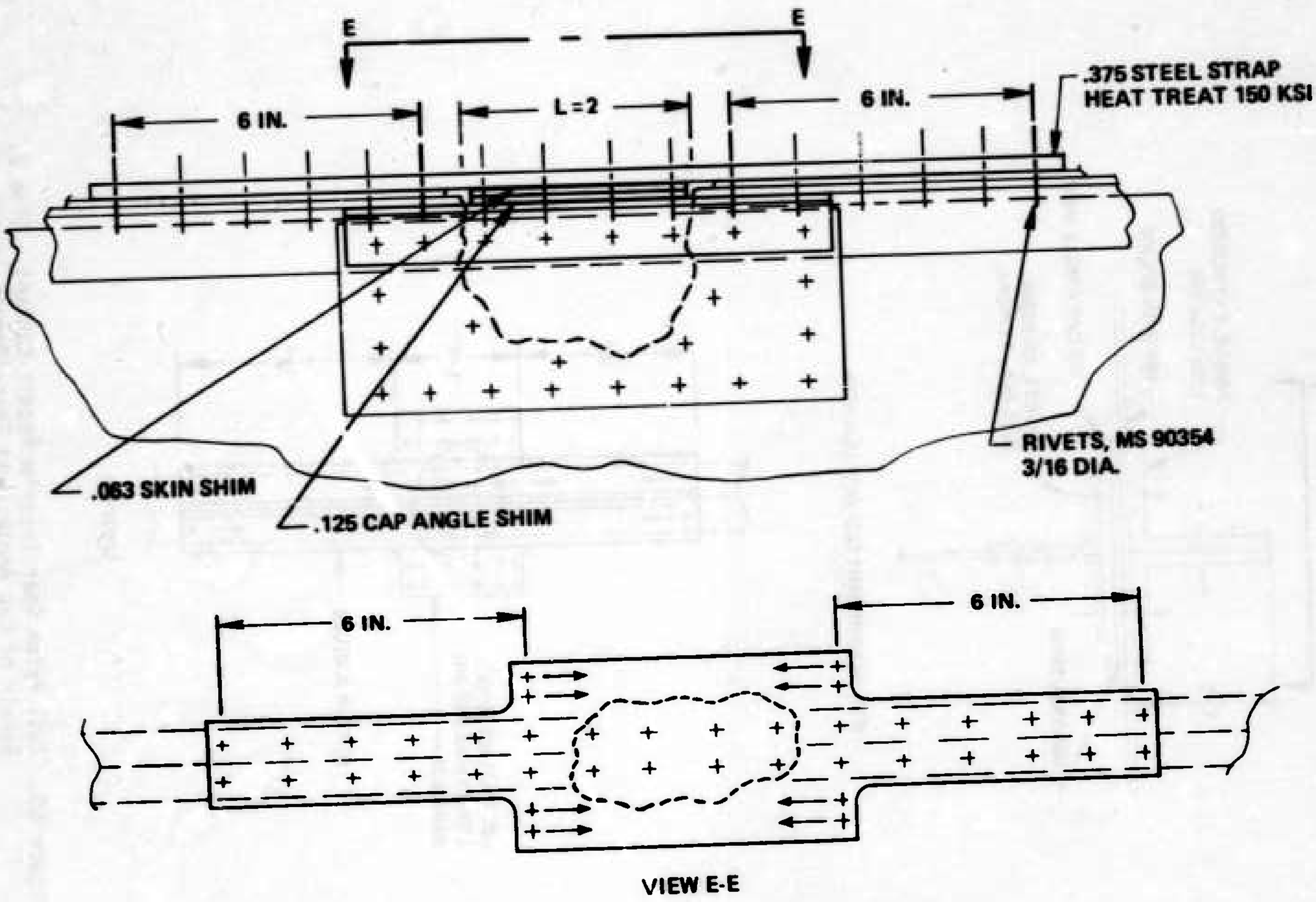

Figure 49. Tail Pylon Spar Interim Repair Concept - Step 2, Repair of Cap Angles and Skin (Damage Length Less than 2 Inches)

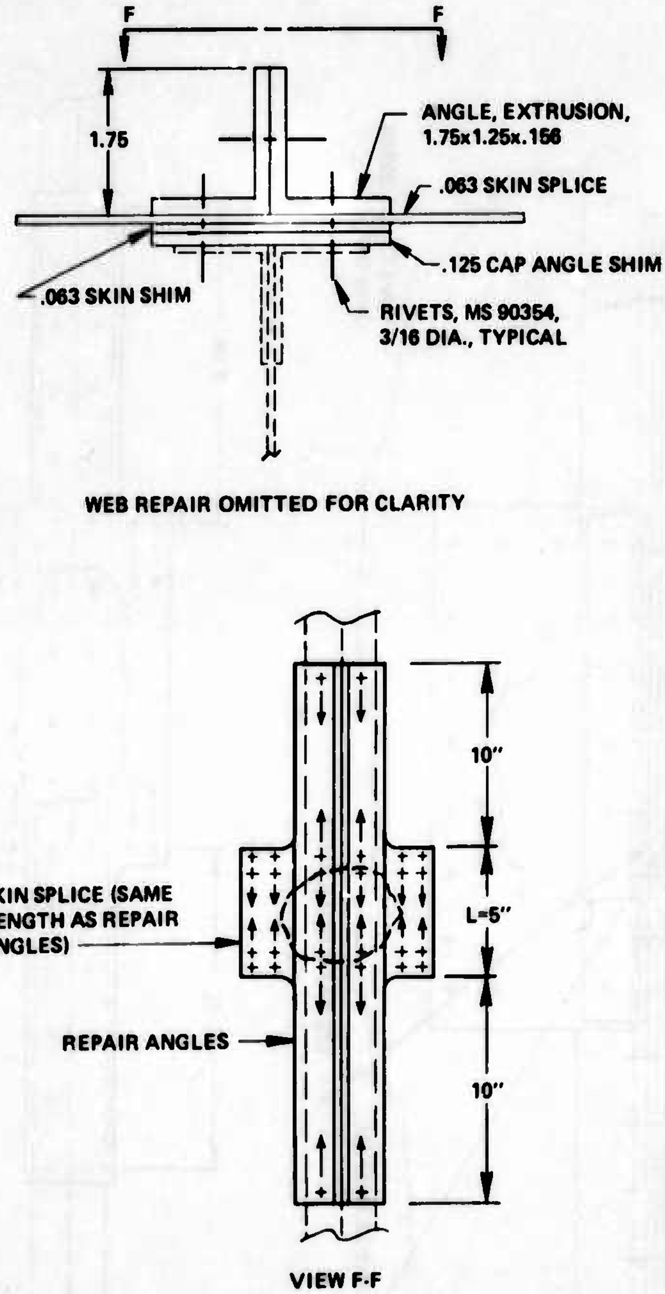

Figure 50. Tail Pylon Spar Interim Repair Concept - Step 2, Repair of Cap Angles and Skin (Damage Length up to 5 Inches)

TAILCONE INTERIM REPAIR CONCEPT

The tailcone is of semi-monocoque, floating-frame construction. Except at one location, the stringers run on the outside of the frame caps with no skin-to-frame attachment. The tailcone frames are formed sheet metal. Formed sheet metal stringers are preassembled to the skin and then attached to the frames. The tailcone is joined to the rear fuselage with 29 bolts, one at each stringer. A forged bathtub fitting is provided at each attachment point to transfer the load from the stringer. Between bolts, Hi-Lok fasteners are used for shear transfer. The tail rotor pylon is joined to the tailcone via a canted hinge bulkhead which permits folding the empennage.

Stringers, frames, and skin panels are the principal elements of the tailcone. The stringers carry the tailcone bending loads. The frames provide column stability to the stringers and overall stability to the structure. The skin panels carry torsion moments and shear loads.

Assumed Damage Condition

The assumed combat damage to the tailcone occurs at the intersection of a frame and stringer (Figure 51). Sections of the frame, stringer, and skin panel are lost. For simplicity, the illustration is confined to a single frame and stringer, but the repair scheme would be applicable to much larger areas of damage involving multiple frames and stringers. In areas of the tailcone where the frames have a pronounced curvature, a slightly different approach to frame repair, probably involving hand-forming of parts, would be necessary.

Objectives

In addition to the objectives common to all interim repairs (avoiding internal access, hand-forming of parts, etc.), the following specific objectives apply to repair of the tailcone:

Stringer Repair

1. Restoration of continuity across the damaged section.

2. Support of tension and compression axial loads due to tailcone bending.

3. If repair is external, sufficient inertia in the repaired section to support loads as an eccentric column.

4. Minimum structural offset

Skin Repair

1. Restoration of continuity across the damaged section

2. Support of shear loads and tension loads

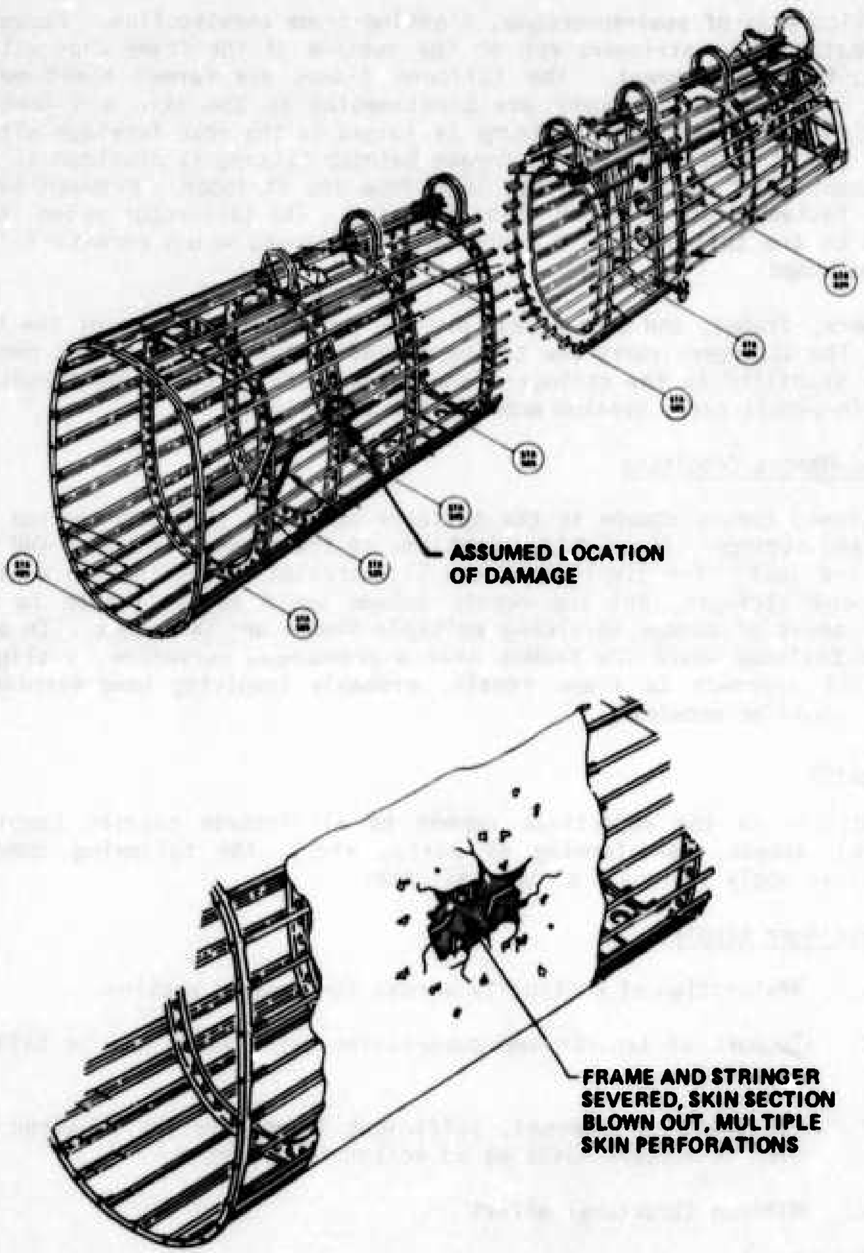

Figure 51. Tailcone Interim Repair Concept - Assumed Location of Damage to Skin, Frame, and Stringer

3. Where feasible, installation of a sufficient number of fasteners to develop the tensile strength of the skin

Frame Repair

1. Restoration of continuity across the damaged section

2. Restoration of the overall shell stability function of the frame

3. Provisions for reattaching stringers to the repaired frame

Repair Concept

In the first step of the repair (Figure 52), a section of skin is removed to provide working access to the damaged frame. This step can be eliminated by having the mechanic gain access to the interior of the tailcone by crawling over the fuel cells in the rear fuselage; however, the difficulty of working in such confined quarters would probably require more time than is required to remove the skin.

In the next step of the repair (Figure 53), the damaged frame is repaired by riveting a 2½-inch-wide channel over the missing section of frame. The use of an external channel saves considerable time versus nesting a channel within the frame as would be required for a conventional repair. The channel may be standard extrusion or an assembly of two extrusions and a flat plate.

In the next step of the repair (Figure 54), the damaged stringer is repaired with extruded angles riveted to each leg of the zee-section. Nested angles are used because removal of the skin section provides adequate access for this type of repair.

In the final step of the repair (Figure 55), the repaired stringer is attached to the repaired frame section and a skin patch is installed with blind rivets. Shims are used to fill gaps between the stringers and the external skin patch.

Repair of Damage to Skin and Stringer

The concept just described would apply where damage to the tailcone involves one or more frames. Where the damage involves skin and stringers only, internal access to the frame is unnecessary and the repair can be further simplified by repairing the stringer externally as shown in Figures 56 and 57.

Evaluation of the Repair Concept

Both versions of the tailcone interim repair concept restore the structure to original strength. It is estimated that the repair involving damage to the frame can be accomplished by two men in approximately 15 hours. Interim repair of the damage involving only the tailcone skin and stringer can be accomplished by two men in an estimated 3 hours.

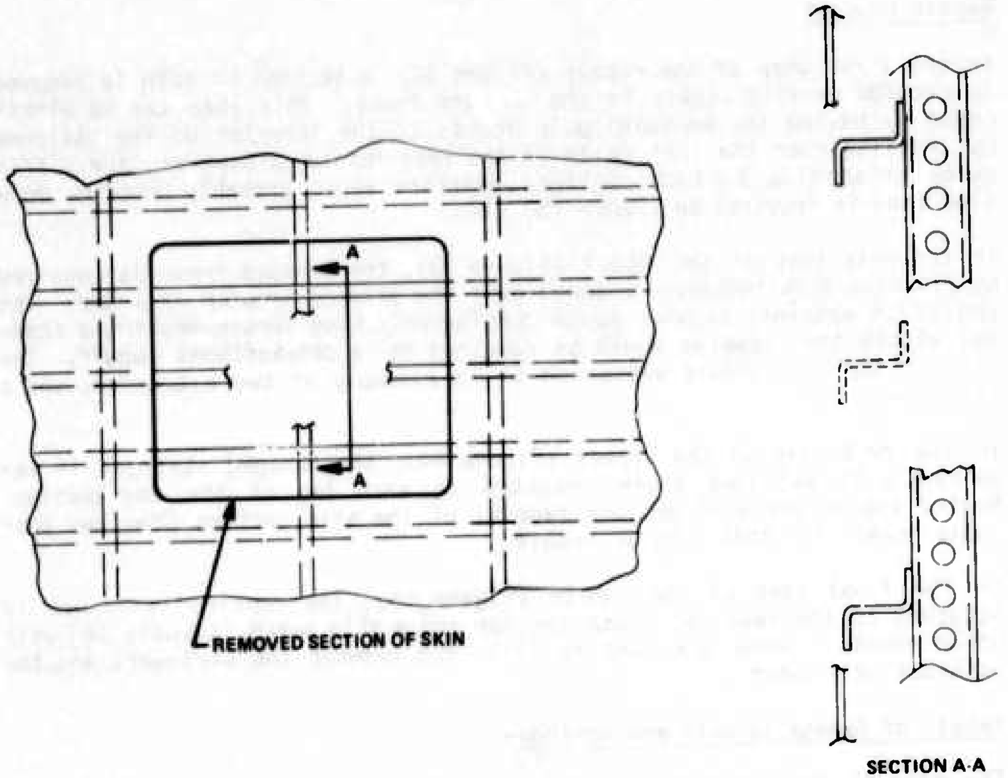

Figure 52. Tailcone Interim Repair Concept - Step 1, Removal of Skin Section for Access to Damaged Frame

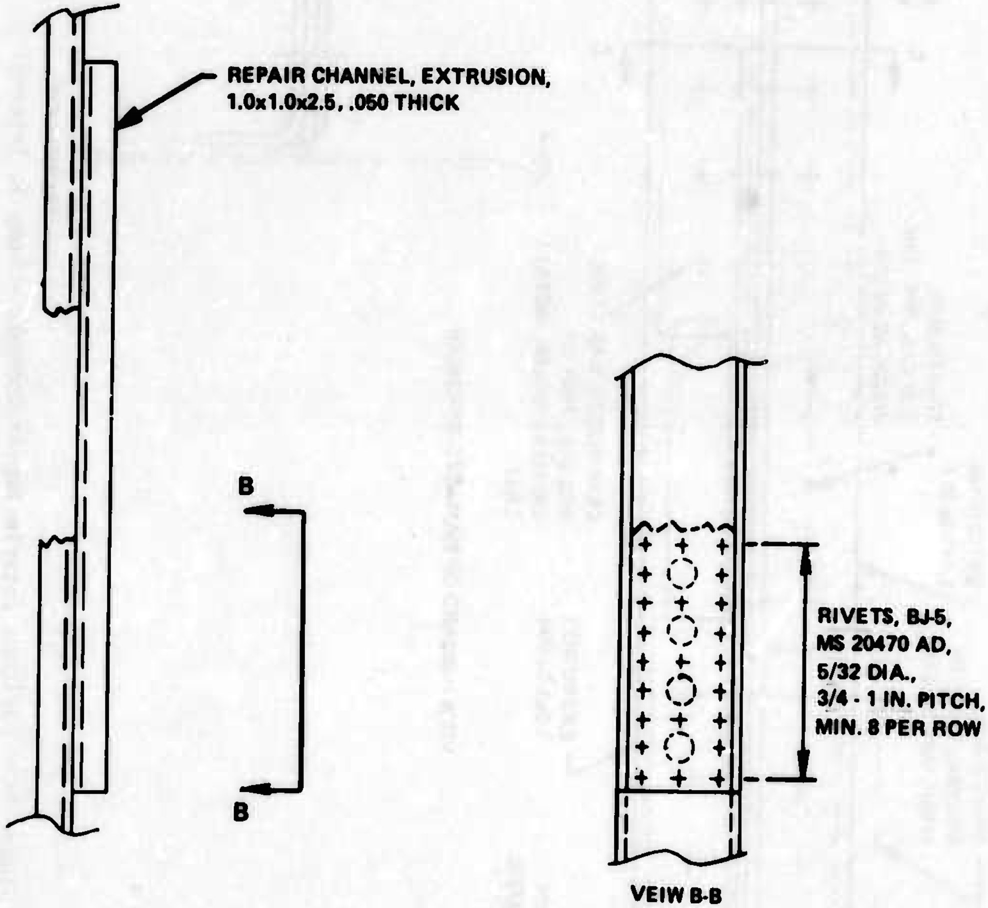

Figure 53. Tailcone Interim Repair Concept - Step 2, Frame Repair

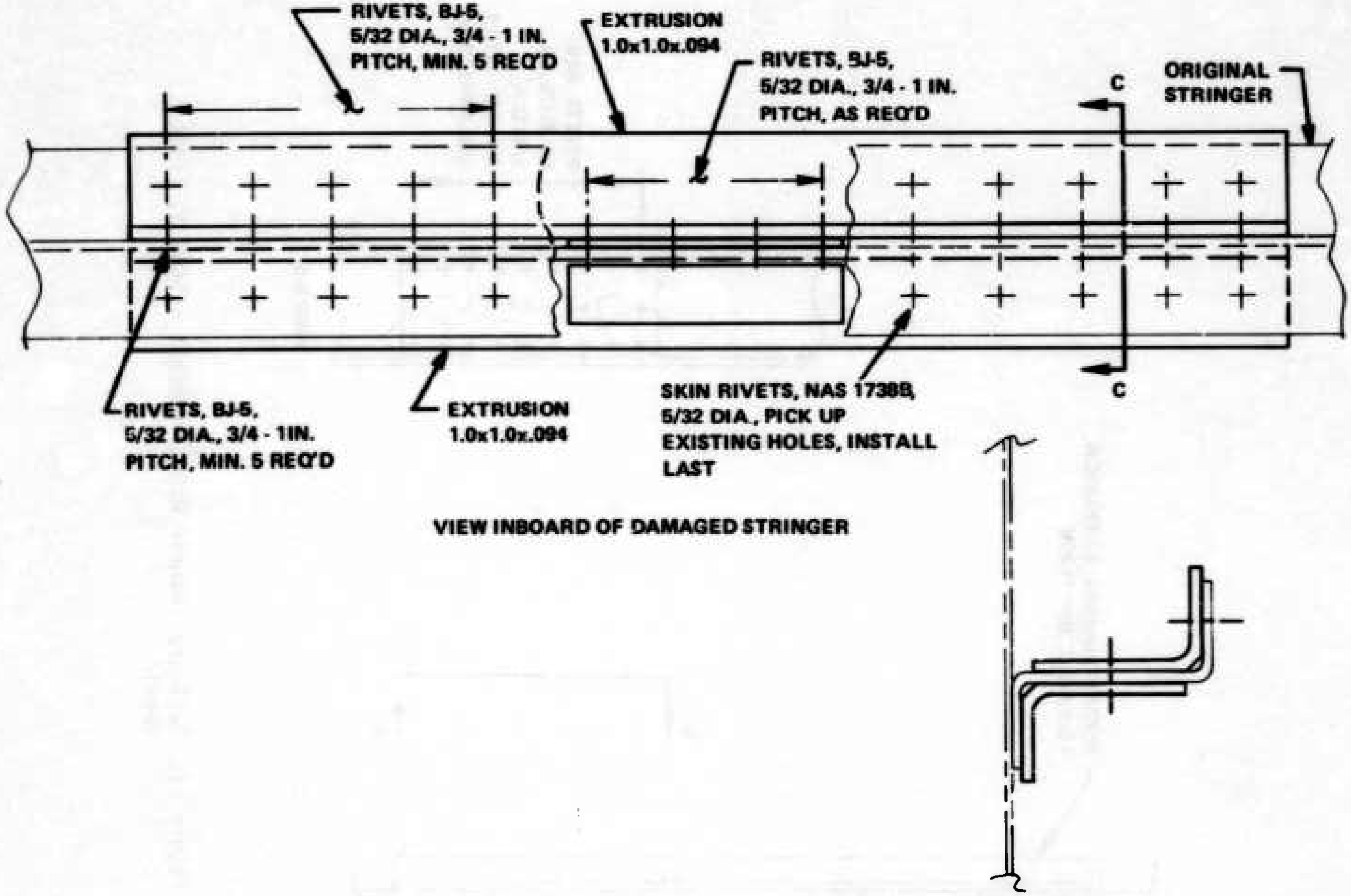

Figure 54. Tailcone Interim Repair Concept - Step 3, Internal Repair of Stringer

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B

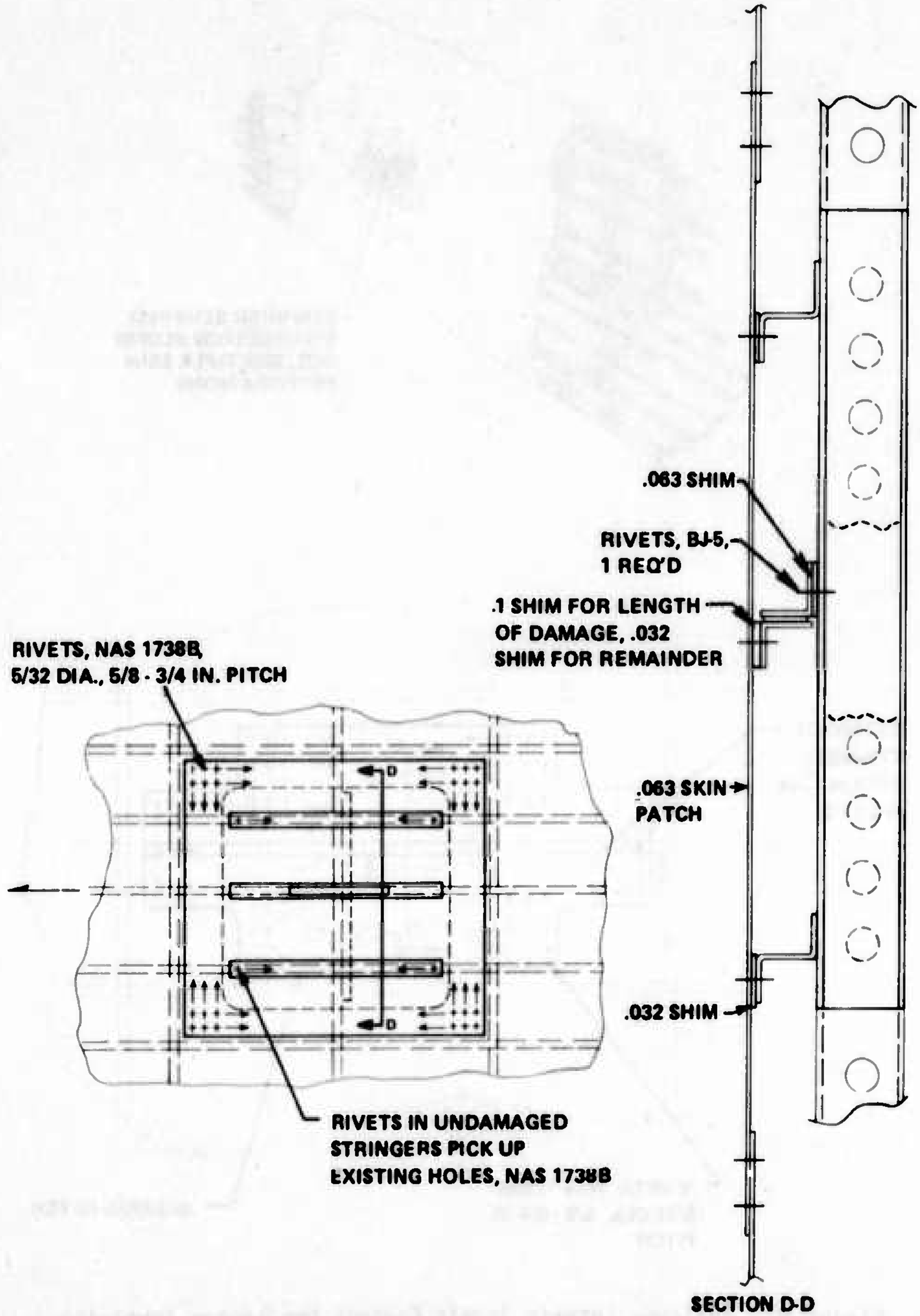


Figure 55. Tailcone Interim Repair Concept - Step 4, Skin Repair

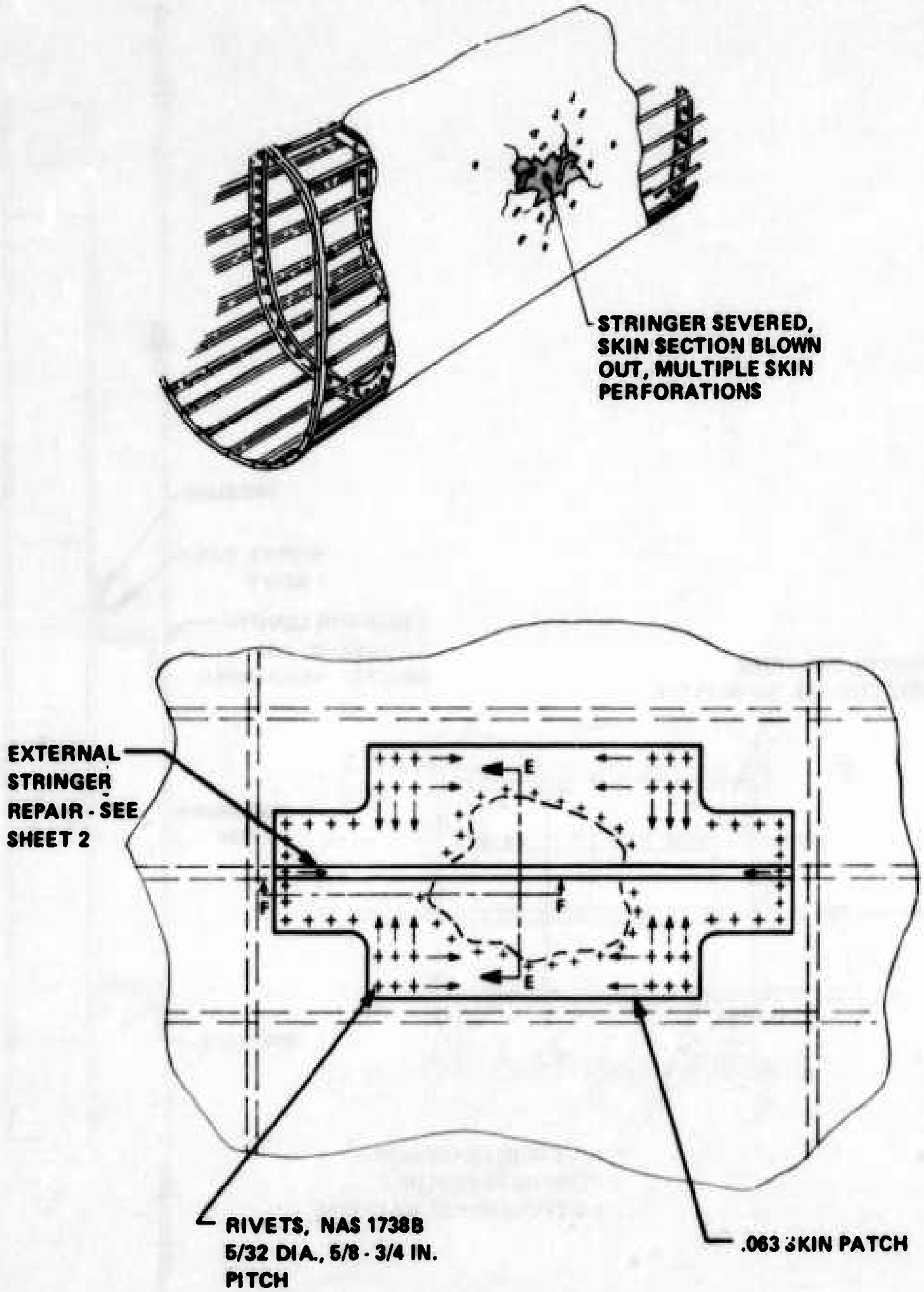


Figure 56. Tailcone Interim Repair Concept for Damage Involving Skin and Stringer Only (1 of 2)

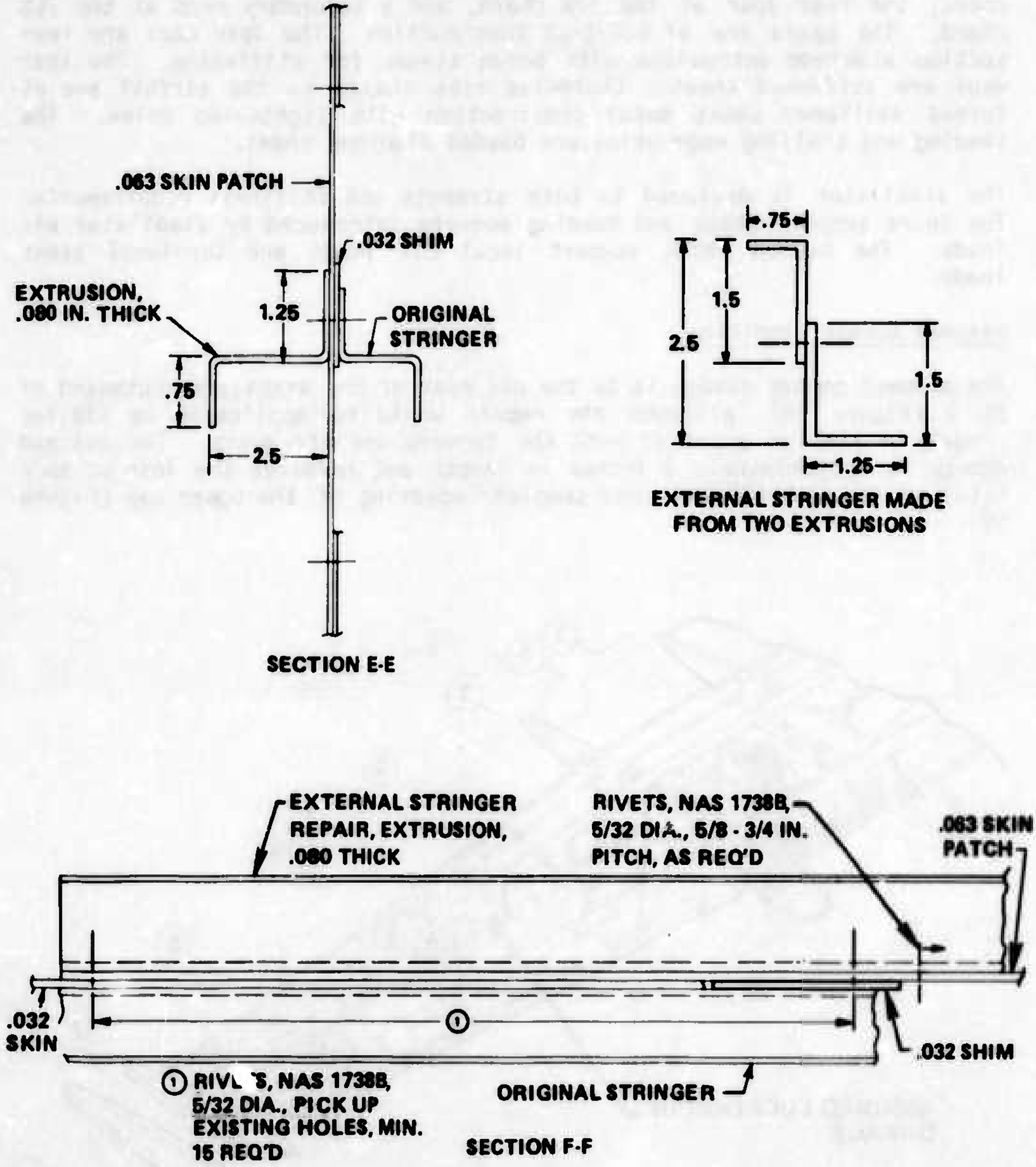


Figure 57. Tailcone Interim Repair Concept for Damage Involving Skin and Stringer Only (2 of 2)

STABILATOR SPAR INTERIM REPAIR CONCEPT

The horizontal stabilator is a two-spar box beam structure supported at the hinge line forward of the front spar and by the hydraulic actuator located between the front and rear spars. The front spar is at the 28% chord, the rear spar at the 57% chord, and a secondary beam at the 75% chord. The spars are of built-up construction. The spar caps are tee-section aluminum extrusions with boron straps for stiffening. The spar webs are stiffened sheet. Chordwise ribs shaped to the airfoil are of formed stiffened sheet metal construction with lightening holes. The leading and trailing edge skins are beaded aluminum sheet.

The stabilator is designed to both strength and stiffness requirements. The spars support shear and bending moments introduced by stabilator air loads. The beaded skins support local air loads and torsional shear loads.

Assumed Damage Condition

The assumed combat damage is to the aft spar of the stabilator outboard of BL 9 (Figure 58), although the repair would be applicable to similar damage to similar areas of both the forward and aft spars. The assumed damage is approximately 3 inches in length and involves the loss of sections of the web and skin and complete severing of the upper cap (Figure 59).

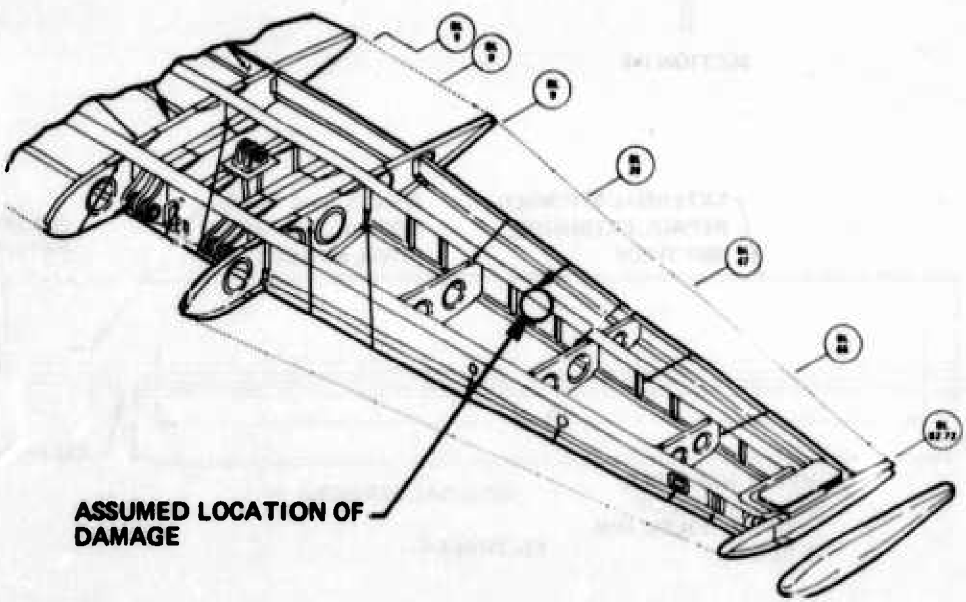


Figure 58. Stabilator Spar Interim Repair Concept - Assumed Location of Damage

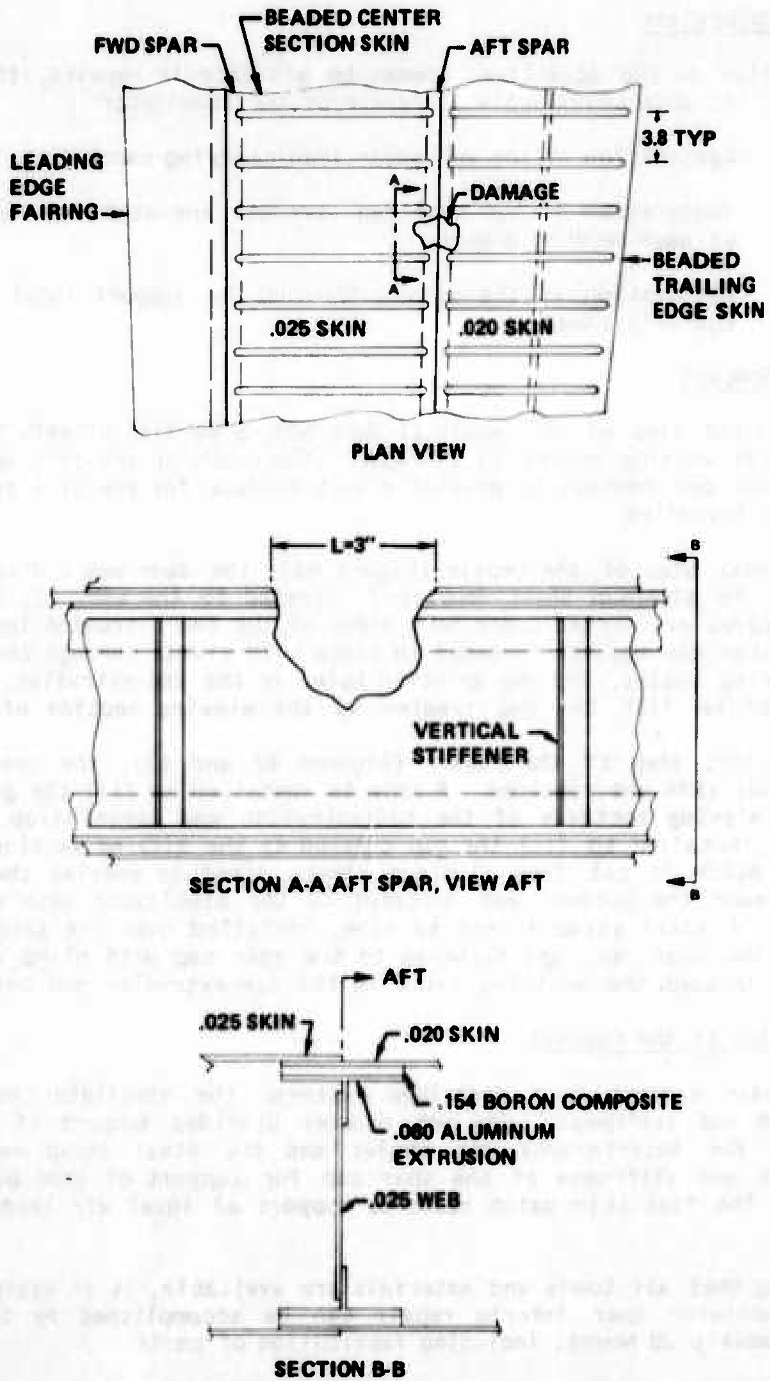


Figure 59. Stabilator Spar Interim Repair Concept - Assumed Area and Extent of Damage

Repair Objectives

In addition to the objectives common to all interim repairs, the following specific objectives apply to repair of the stabilator:

1. Restoration of the web shear load-carrying capability

2. Restoration of the spar cap strength and stiffness for support of beam bending moments

3. Restoration of the skin sufficient to support local air loads and skin shears

Repair Concept

In the first step of the repair (Figure 60), a section of skin is removed to provide working access to the spar. The beads on the skin adjacent to the cutout are removed to provide a flat surface for the skin patch which is later installed.

In the next step of the repair (Figure 61), the spar web and cap are repaired. An aluminum sheet doubler is riveted to the web. Extruded aluminum angles are nested under both sides of the tee-extrusion incorporated in the spar cap and are fastened in place with rivets through the doubler, reinforcing angles, and the existing holes in the tee-extrusion. A shim is installed to fill the gap created by the missing section of the web.

In the last step of the repair (Figures 62 and 63), the spar cap and stabilator skin are repaired. A shim is installed to fill the gap created by the missing sections of the tee-extrusion and boron strap. Another shim is installed to fill the gap created by the missing section of skin. A skin patch is cut from aluminum sheet, sized to overlap the existing skin around the cutout, and fastened to the stabilator skin with blind rivets. A steel strap is cut to size, installed over the skin patch on top of the spar cap, and fastened to the spar cap with blind rivets installed through the existing holes in the tee-extrusion and boron strap.

Evaluation of the Concept

The repair concept just described restores the stabilator to original strength and stiffness. The web doubler provides support of web shear loads. The back-to-back cap angles and the steel strap restore the strength and stiffness of the spar cap for support of beam bending moments. The flat skin patch restores support of local air loads and skin shears.

Assuming that all tools and materials are available, it is estimated that the stabilator spar interim repair can be accomplished by two men in approximately 20 hours, including fabrication of parts.

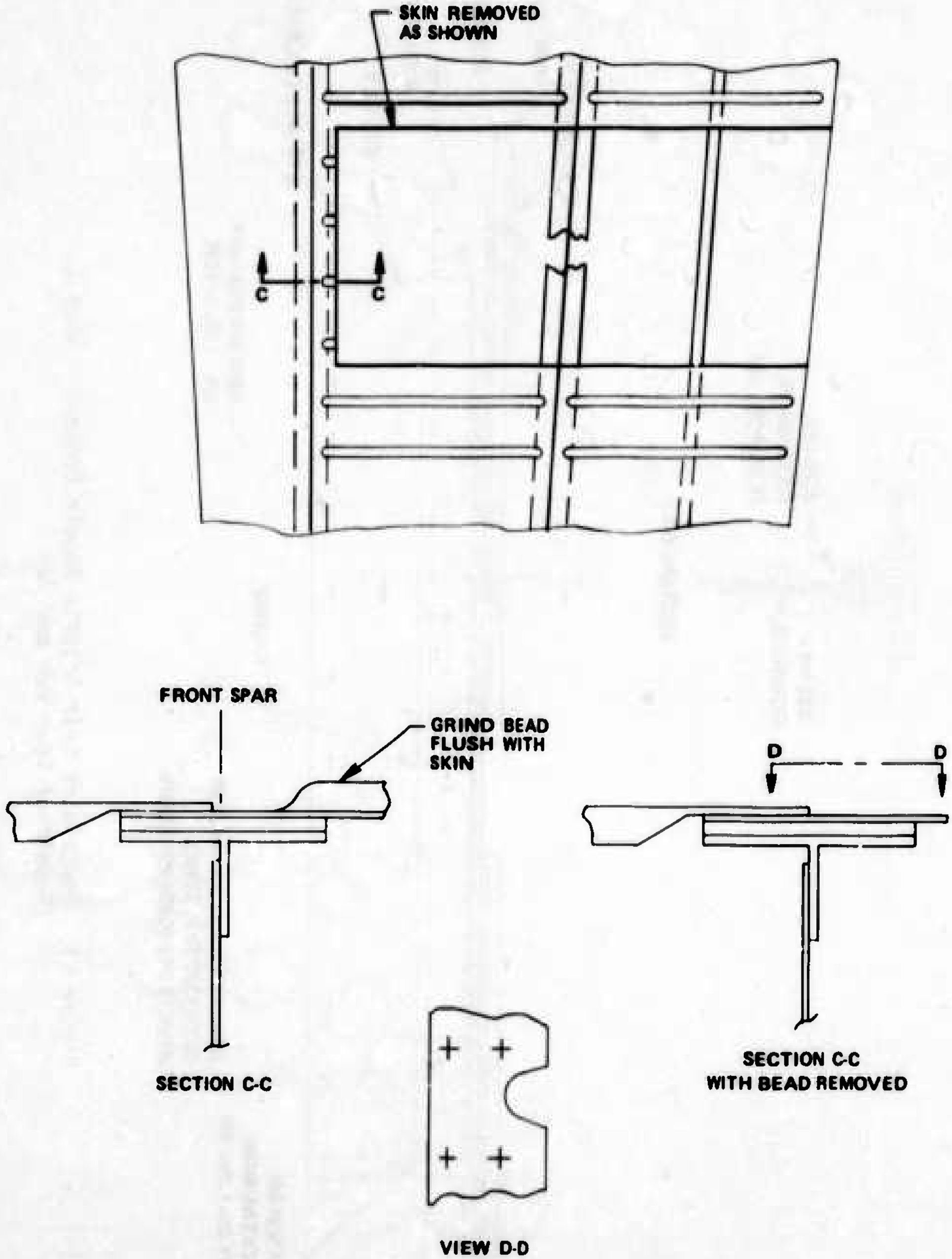


Figure 60. Stabilator Spar Interim Repair Concept - Step 1, Removal of Skin Panel and Beads

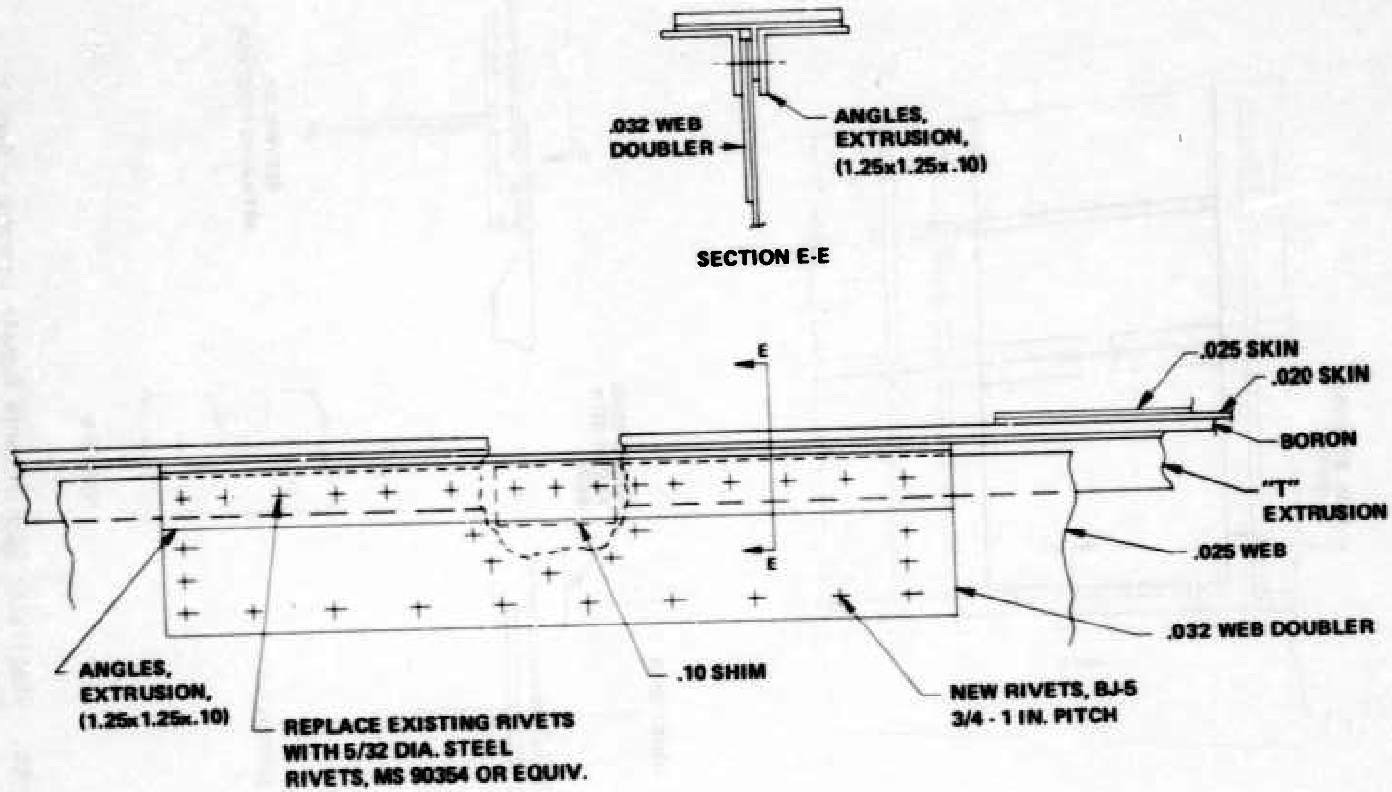


Figure 61. Stabilator Spar Interim Repair Concept - Step 2, Repair of Spar Web and Cap

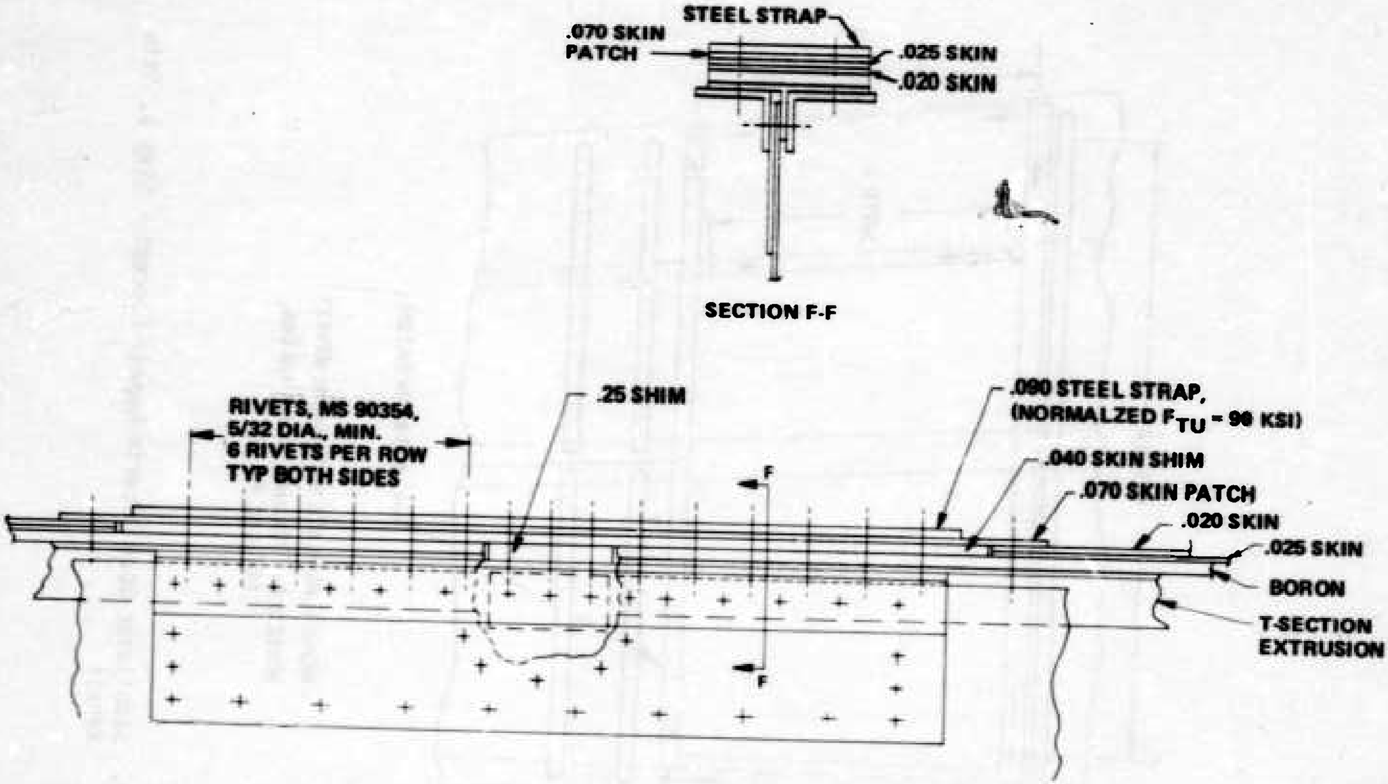
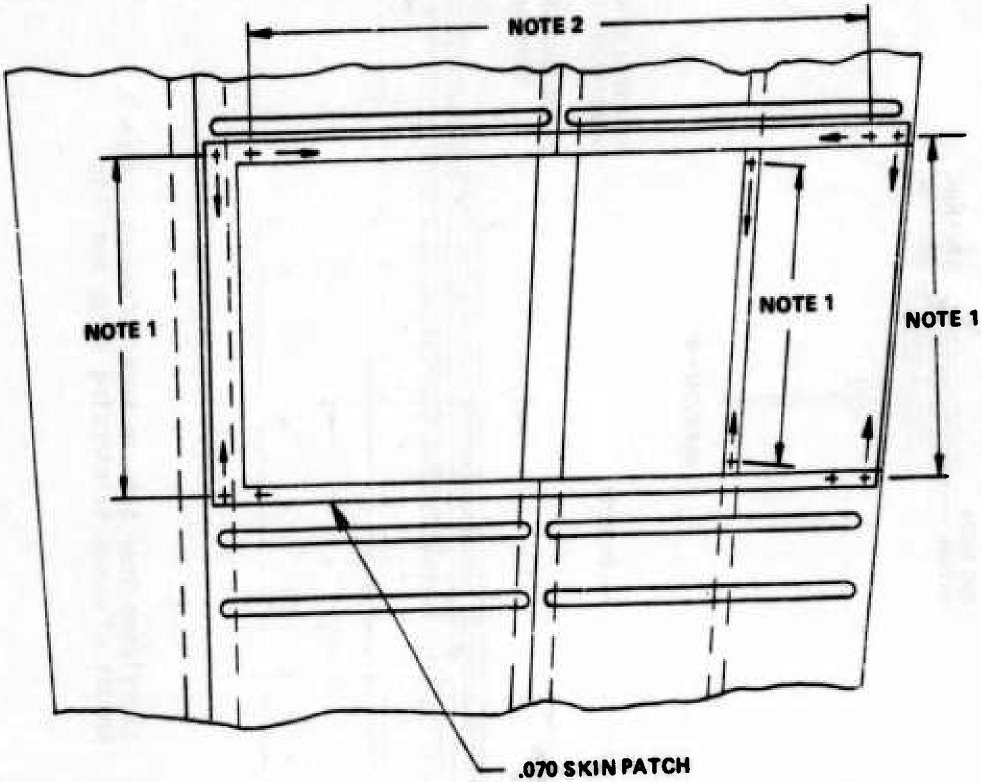


Figure 62. Stabilator Spar Interim Repair Concept - Step 3, Repair of Boron Reinforcing Strap and Skin



NOTE 1: REPLACE WITH SAME RIVETS

NOTE 2: RIVETS, NAS 173[illegible], 1/8 DIA., 7/8 - 1 IN. PITCH

Figure 63. Stabilator Spar Interim Repair Concept - Step 3, Skin Repair

CABIN MAIN FRAME INTERIM REPAIR CONCEPT

The upper section of the cabin main frame at Sta. 308 is a single-piece machined forging that extends partially down the sides of the fuselage where it is joined to the side fittings with high-strength fasteners. It has tee-section caps and integrally stiffened webs. The integral machined stiffeners provide lateral stability to the frame web and support frame cap loads due to change of direction of the frame flanges. The Sta. 308 frame is the most heavily loaded frame in the fuselage. Design loading conditions include main transmission support loads and main landing gear loads. The frame also contributes significantly to overhead stiffness requirements. The primary internal frame loads are:

1. In-plane bending moments supported by the outboard and inboard frame caps.

2. Shear loads supported by the frame web.

3. Axial loads supported by both the frame web and the frame caps.

Assumed Damage Condition

The assumed damage involves the loss of a section of the Sta. 308 frame cap and web at approximately B.L. 26 (Figure 64). Approximately 1½ inches of the lower cap is missing and the damage extends approximately 1½ inches into the web (Figure 65). Damage involving a substantially larger section of the web would probably be repairable, but substantially larger damage to the frame cap would likely create problems of misalignment that would require jigging to repair. The damage is assumed to be in a relatively straight section of the frame. Further outboard where the frame is curved, repair would be more difficult, probably requiring hand-forming and fitting of parts.

Repair Objective

Due to the structural importance of the Sta. 308 frame, restoration of original strength and stiffness is a primary objective of the repair.

Repair Concept

In the first step of the repair (Figure 66), the damage area is cleaned to remove all sharp edges. The integral stiffeners on the forward and aft sides of the frame outboard of the damage are ground flush with the web to provide a flat surface for installation of the repair. Enough of the stiffener is removed to permit installation of the web doubler on the forward side and the cap angle on the aft side.

A web doubler is cut from steel plate and fastened to the web with high-strength fasteners. The fasteners are omitted where the cap strap and angles and the stiffener angle are to be subsequently installed.

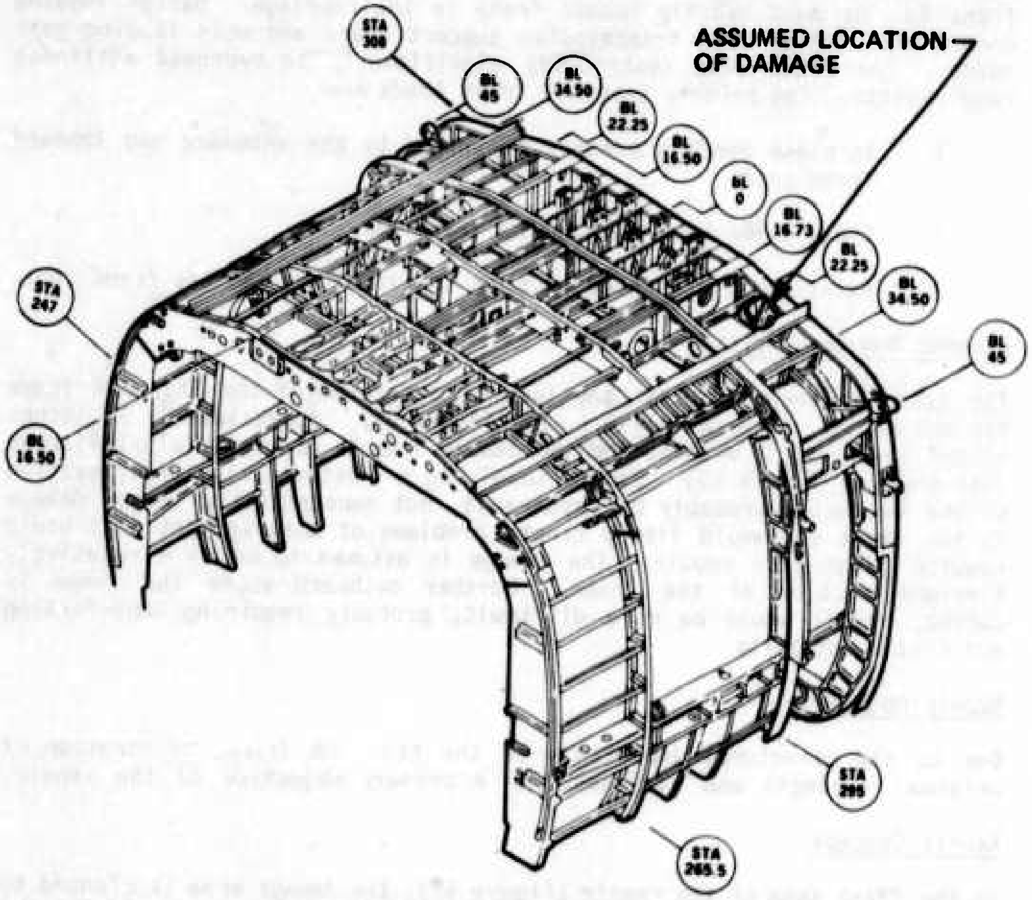


Figure 64. Cabin Main Frame Interim Repair Concept - Assumed Location of Damage

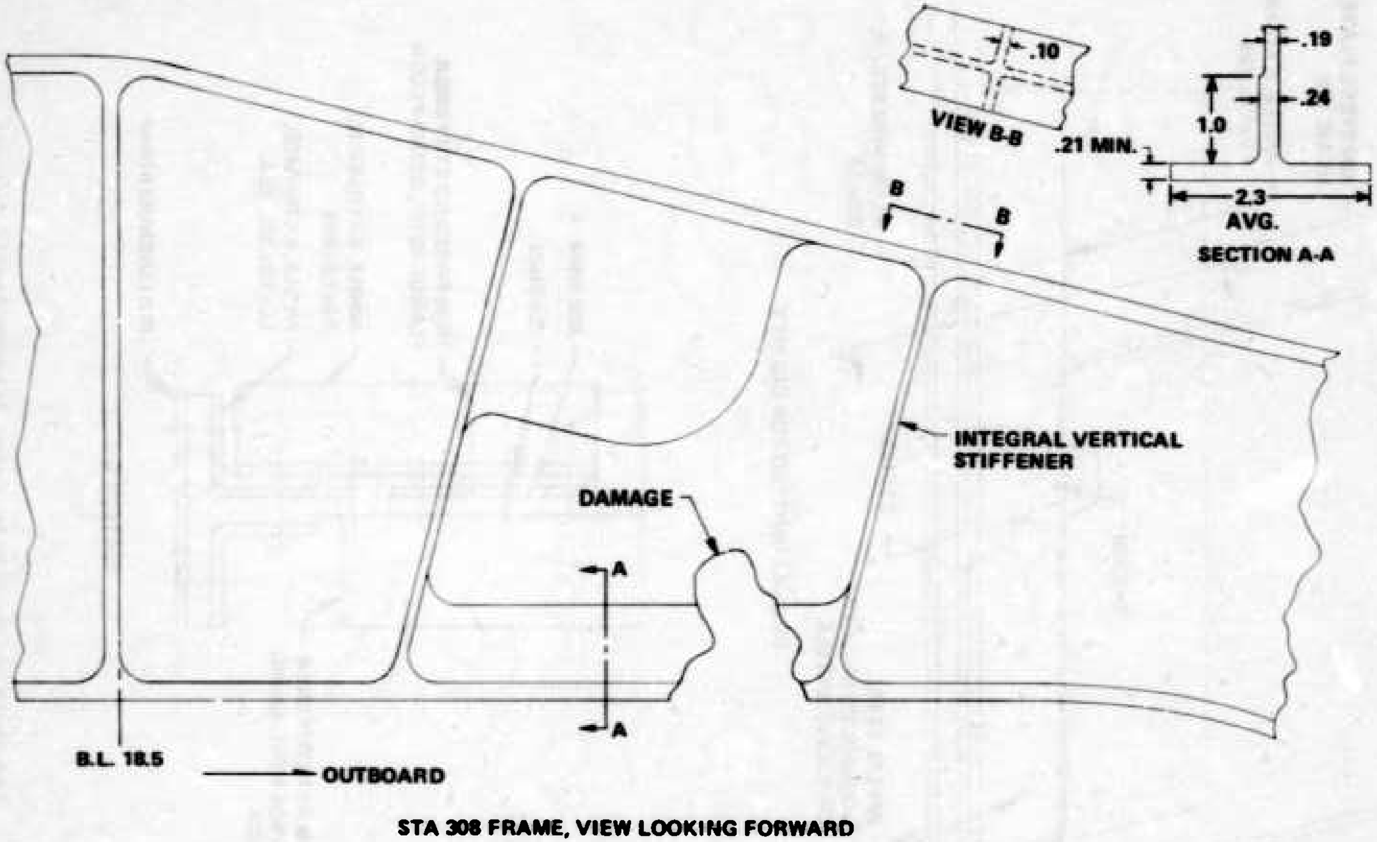
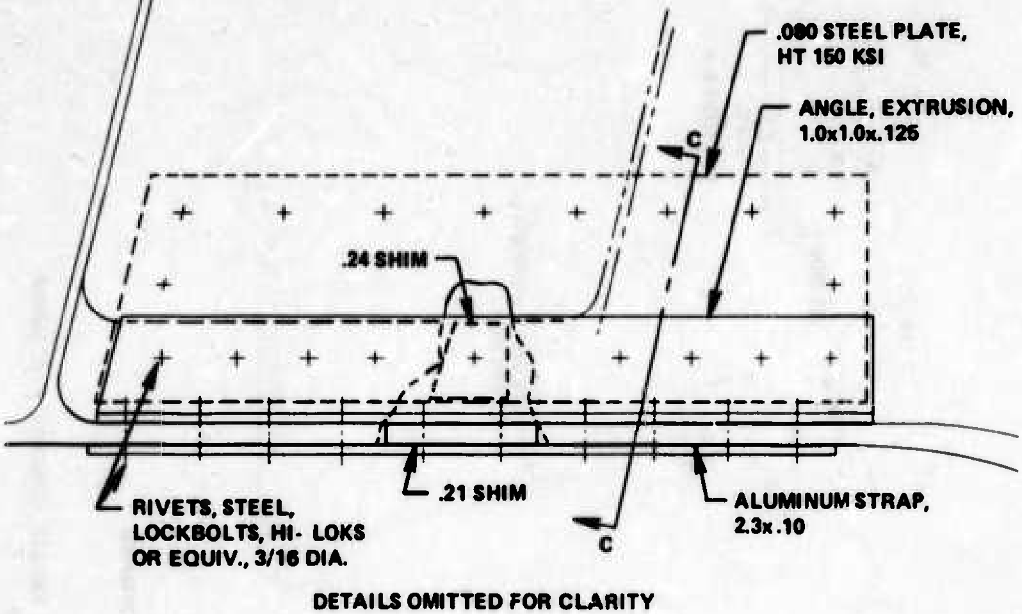


Figure 65. Cabin Main Frame Interim Repair Concept - Assumed Area and Extent of Damage



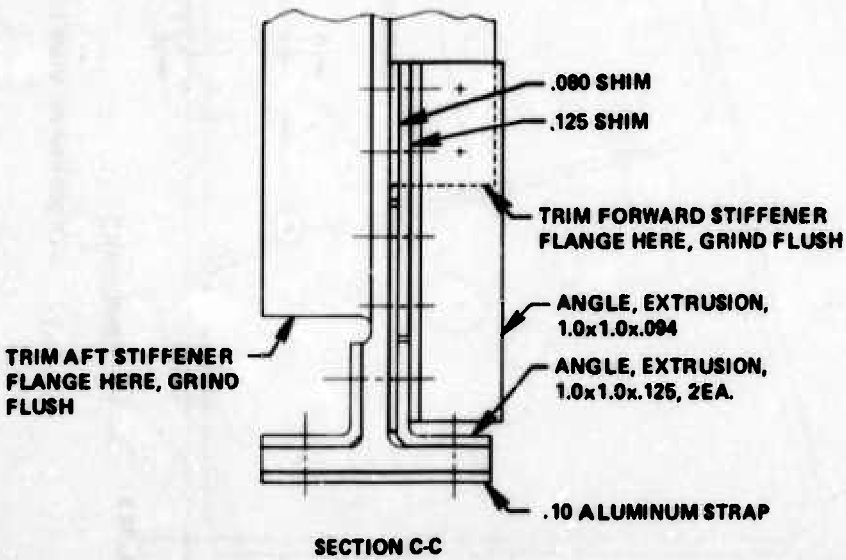


Figure 66. Cabin Main Frame Interim Repair Concept

A strap is cut from aluminum sheet and fastened to the frame cap together with two extruded aluminum angles as shown in Figure 66. Using shims to fill gaps between parts, an extruded aluminum angle is installed to beef up the partially removed stiffener on the forward side of the frame.

Evaluation of the Repair

The back-to-back angles and the strap restore full strength and stiffness to the frame cap. The steel doubler restores full shear and axial load strength and stiffness to the frame web. The angle on the forward side of the frame restores stiffener continuity across the repaired area.

Assuming that all tools and materials are available, it is estimated that the cabin frame interim repair can be accomplished by two men in approximately 4 hours, including fabrication of parts.

OVERALL EVALUATION OF REPAIR CONCEPTS

The interim repair concepts described in the preceding pages achieve a significant reduction in repair time versus that required for standard repairs of these components. This is achieved primarily by applying external repairs that avoid the need for internal access to damaged structure and by using standard structural shapes in lieu of hand-formed parts. Nesting of repair parts within damaged members, the conventional method of repair, is also avoided in cases where interior surfaces are not readily accessible. With these exceptions, the repairs employ commonly available tools and materials and standard sheet metal repair techniques.

The use of bonded composites for repair of primary metal structures was considered. Significant problems were encountered with this approach, however. First is the difficulty of matching the mechanical properties (strength, modulus, etc.) of the parent structure. A quasi-isotropic layup of unidirectional graphite could achieve mechanical compatibility with primary aluminum structure but would introduce these problems: Although not of major concern for an interim (temporary) repair, graphite and aluminum are not chemically compatible and, unless the two materials are isolated, corrosion will develop over time. Unless precured material is used, laying up the graphite at the site will probably be more time-consuming than fabricating metal parts. The use of precured composite material would avoid the time-consuming layup but would also preclude forming repair parts on the site as is easily done with aluminum.

The overriding concern with the use of composites for repairing primary metal structure is that of achieving quality bonding in a field environment, especially the combat environment. Unless strict environmental and process control are maintained, achieving consistent quality is virtually impossible. Also, unlike a mechanically installed repair whose quality can be easily verified by inspection, there may be no way to verify the quality of a composite-to-metal bonded repair in the field. The risk of the repair failing in service is therefore much greater with bonds than with mechanical fasteners.

Lastly, the use of composites for repair of primary metal structures in combat would introduce techniques, tools, and materials with which the average structural repairman will have acquired no experience in peacetime. Proficiency with these techniques could not be expected. For all of the above reasons, the use of composites was not pursued.

Two of the interim repair concepts developed in this program meet the Army's mean repair time objective of 5 hours. The remaining concepts meet the maximum repair time objective of 24 hours. All four concepts address significant damage to heavily loaded primary structure. It appears that the methods considered in this program can expedite return to service of combat-damaged aircraft. Versus other systems of the aircraft which are comprised of easily replaceable components, however, the airframe can still be expected to be among the major contributors to aircraft downtime in combat.

COMBAT MAINTENANCE SUPPORT CONCEPTS

AIRFRAME COMBAT DAMAGE REPAIR

Within the present state of the art, it appears that repair of helicopter airframes in combat will employ materials, tools, and skills similar to those used in peacetime maintenance of the aircraft. Airframe repairs in combat may involve a substantial relaxation of the requirements imposed on maintenance organizations in peacetime but, based on this study, probably will not differ significantly with respect to detail methods. It is expected that the ratio of structural repairmen to other types of maintenance skills will vary substantially in combat versus peacetime.

In peacetime, most airframe maintenance in the field is of a nuisance variety; major airframe repairs are rarely required. In combat, particularly with highly survivable aircraft such as Black Hawk, major airframe damage will be among the most frequent damage the helicopter will suffer and also among the most difficult and time-consuming to repair. Combat damage repair of the airframe will require proportionately more repairmen than most other systems of the aircraft and may require more advanced training than these personnel now receive. An investigation of this need is covered in the Recommendations section of this report.

AIRFRAME COMBAT DAMAGE ASSESSMENT

Two approaches might be considered for assessment of airframe damage in combat. The first would be to develop a specialist MOS devoted exclusively to this function. The alternative would be to train an existing MOS to perform these duties.

The advantage of the first approach is that personnel dedicated to the task of damage assessment should be more highly skilled at that work than personnel for whom damage assessment is a part-time duty. There are also major disadvantages with the specialist approach, however. First, combat damage assessment is not a function that is performed in peacetime and it will be difficult for specialists to maintain proficiency. It will also be difficult to simulate for training purposes the large variety of airframe damage that will be experienced in combat. Also, having trained specialists in the maintenance organization who have no productive role in peacetime will be costly. Finally, there is the concern associated with creating small numbers of specialists who may be lost or incapacitated in combat.

If it is feasible to do so, the alternative approach of training an existing MOS to perform combat damage assessment would avoid many of these problems. Combat damage assessment is a crucial undertaking, however, and it is uncertain whether maintenance personnel can acquire the necessary skills as an adjunct to their regular duties. Since the work basically involves inspection, the Technical Inspector (TI) is the logical candidate to consider for this assignment. A program to explore the feasibility of this approach is covered in the Recommendations section of this report.

The combat damage assessment technique developed in preliminary form under this program has the potential for greatly simplifying assessment of combat damage. If through further development work this potential is realized, it is believed that the task of combat damage assessment can be absorbed by the TI. He will require a brief course of training in the use of the technique and occasional practice in its application. With this, it is believed that the TI can acquire and retain the necessary skills. Further development and testing of the combat damage assessment technique is covered in the Recommendations section of this report.

COMBAT REPAIR KITS

Although the methods of combat damage repair described in this report employ standard tools and materials, combat repair efficiency might be enhanced by packaging some of these materials in special repair kits. Instead of requiring the repairman to draw materials from bulk supply and cut individual parts from large pieces of stock, frequently used materials might be supplied in kit form. The kits would contain such materials as aluminum sheet, extrusions, and shim stock of the most frequently required lengths and gages. An analysis would be needed to determine the content of the kits, based on the relative volume of various types of structure in the airframe, their vulnerability to damage, and the shapes and sizes of the materials that would be used to repair them. The analysis might show that several different repair kits would be desirable, one for repair of skin/stringer construction, one for repair of major frames and beams, etc.

CONCLUSIONS

1. The modeling techniques used in this program are an effective method of estimating ballistic damage effects and assessing combat damage repairability.

2. Based on the sample of simulated combat damage cases analyzed in this program, it will be possible to defer repair of the great majority of single-hit ballistic strikes on the Black Hawk helicopter airframe. Repair of the majority of API projectile damage will be deferrable indefinitely with no aircraft operating restrictions. Deferred repair of a large percentage of HEI projectile damage will probably limit the aircraft to a restricted flight envelope.

3. The combat damage assessment technique developed in preliminary form under this program has the potential for greatly simplifying the assessment of airframe combat damage in the field. It is anticipated that the aircraft Technical Inspector can be trained to perform this function.

4. Interim repair techniques can significantly expedite repair of combat-damaged airframes. Despite the reduced repair time that these techniques offer, airframe repair will probably be a major contributor to aircraft downtime in combat.

5. Interim repair of primary airframe structures will primarily utilize existing materials, tools, and techniques. The use of composite materials for repair of primary metal structure does not appear to be feasible.

6. General principles and guidelines can be established for the development of combat damage assessment criteria and combat damage repair techniques. Assessment criteria and repair techniques will have to be tailored to individual aircraft, however.

FUTURE PROGRAM RECOMMENDATIONS

It is recommended that future R&D in the field of combat maintenance be directed toward development of a Combat Maintenance Engineering Guide for Army Aircraft. The guide will provide Army managers and aircraft contractors with a comprehensive set of policies, criteria, and engineering guidelines for maintenance and repair of aircraft in combat. It will enable the Army to contract with the manufacturers to produce combat maintenance manuals and combat support systems for fleet aircraft. A proposed sequence of R&D activities leading to publication of the Combat Maintenance Engineering Guide is shown in Figure 67.

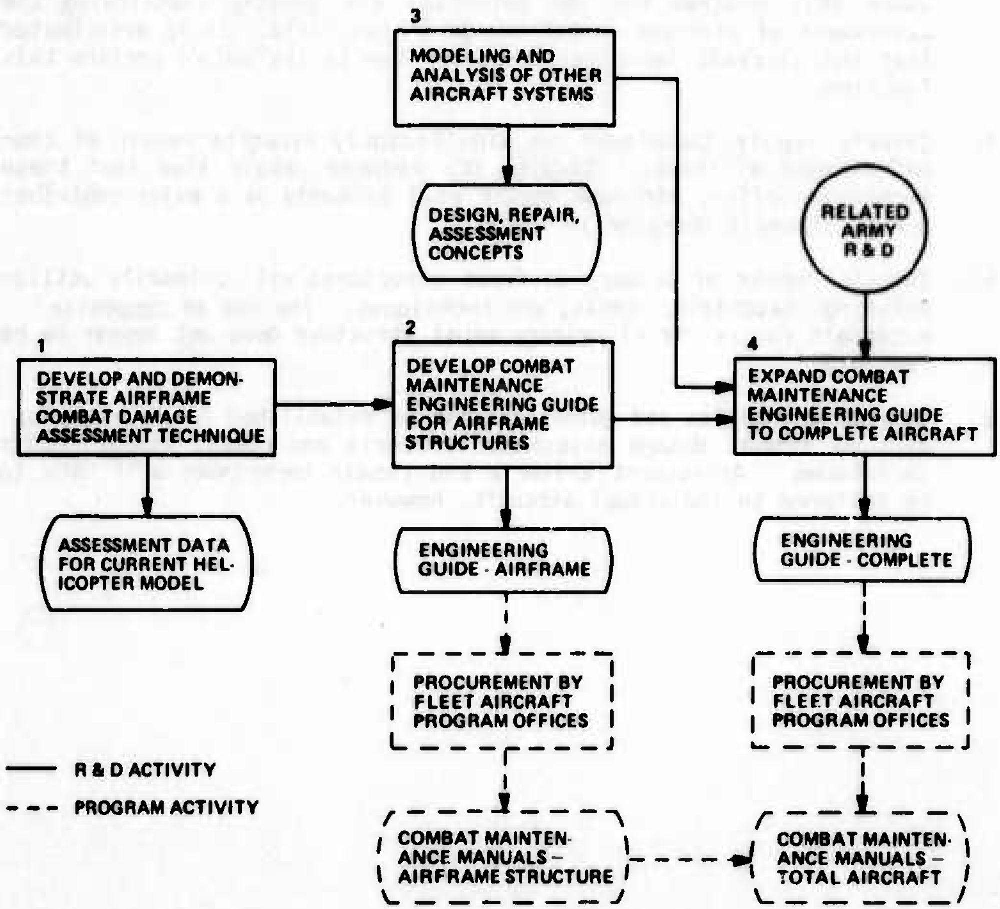


Figure 67. Recommended R&D Program Flow

The engineering guide is developed in several stages, the scope, content, and products of which are listed briefly below. More complete descriptions follow.

Stage 1. A program is undertaken to fully develop and demonstrate the combat damage assessment technique for airframe structures. Assessment criteria and procedures are developed for one of the Army's current inventory aircraft.

Stage 2. A program is undertaken to develop policies, criteria, and engineering guidelines for inspection, assessment, and field repair of airframe combat damage. A Combat Maintenance Engineering Guide for Airframe Structures is developed. The guide is used by Army program offices to procure Airframe Combat Maintenance Manuals for fleet aircraft.

Stage 3. The modeling and analysis techniques developed under the current program are used to analyze requirements and develop concepts for combat maintenance of other helicopter systems. Concepts for assessing and repairing system damage are developed, together with concepts for improving the combat damage repairability of the helicopter through design.

Stage 4. The results of the Stage 3 program are used to complete the Combat Maintenance Engineering Guide. The guide is used by the Army program offices to procure complete Combat Maintenance Manuals for fleet aircraft.

STAGE 1 - COMBAT DAMAGE ASSESSMENT TECHNIQUES

In the first stage of the proposed R&D, it is recommended that the Army fully develop and test the combat damage assessment technique conceived under this program. The purpose of the proposed program will be to verify that damage assessment criteria can be developed for the spectrum of airframe structures and that Army field personnel can be trained to apply the technique with accurate and consistent results. If funding permits, it is proposed that the program include development of complete damage assessment criteria and procedures for the airframe of one of the Army's current inventory aircraft. The recommended tasks are outlined below:

Task I - Expand Assessment Technique

Task II - Identify and Acquire Ballistic Damage Specimens

a. Existing Test Specimens
b. Low-Cost Candidates for Damage Via Ballistic Impact

Task III - Develop Representative Criteria

a. Failure Criteria
b. Repair Deferrability Limits
c. Damage Scoring Criteria

Task IV - Prepare Handbook-Type Graphics and Instructions

Task V - Conduct Demonstrations

a. Train Army TIs
b. Observe Tests by Army TIs
c. Evaluate Results

Task VI - Modify/Refine Assessment Methodology

Task VII - Prepare Combat Damage Assessment Manual for Complete Helicopter Airframe

In Task I, an investigation is made of variations in the combat damage assessment technique that might be required to accommodate significantly different sections of the airframe other than the tailcone type of structure around which it was developed. In Task II, representative items of ballistically damaged airframe structure are identified and acquired. These may be existing items from previously conducted tests or items available at low cost that can be ballistically damaged for the program. In Task III, damage assessment criteria are developed for the structures obtained in Task I. This includes go/no-go failure criteria for individual structural members, point limits for the three categories of repair deferrability, and damage scoring point systems for the structures. In Task IV, the damage assessment criteria are translated into graphics and instructions representative of those contained in Army technical manuals.

In Task V, Army Technical Inspectors (TIs) are trained in the use of the damage assessment technique. The TIs use the technique to assess the deferrability of damage to the airframe structures obtained in Task II. The tests are observed by contractor personnel and the results are evaluated.

In Task VI, the damage assessment technique and formats are modified or refined where indicated by the test results. Task VII concludes the program with the development of a combat damage assessment manual for the primary airframe structures of a current-inventory Army helicopter.

A preliminary schedule and estimate of man-hours for a program of this scope is given in Figure 68.

STAGE 2 - COMBAT MAINTENANCE ENGINEERING GUIDE - AIRFRAME STRUCTURES

As emphasized at the outset, it is recommended that future R&D have the ultimate goal of producing a Combat Maintenance Engineering Guide for Army Aircraft. Because of the sizeable contribution that airframe structural repair is expected to make to the overall maintenance workload in combat, and the progress already made in the area of airframe damage assessment and repair, it is recommended that the Combat Maintenance Engineering

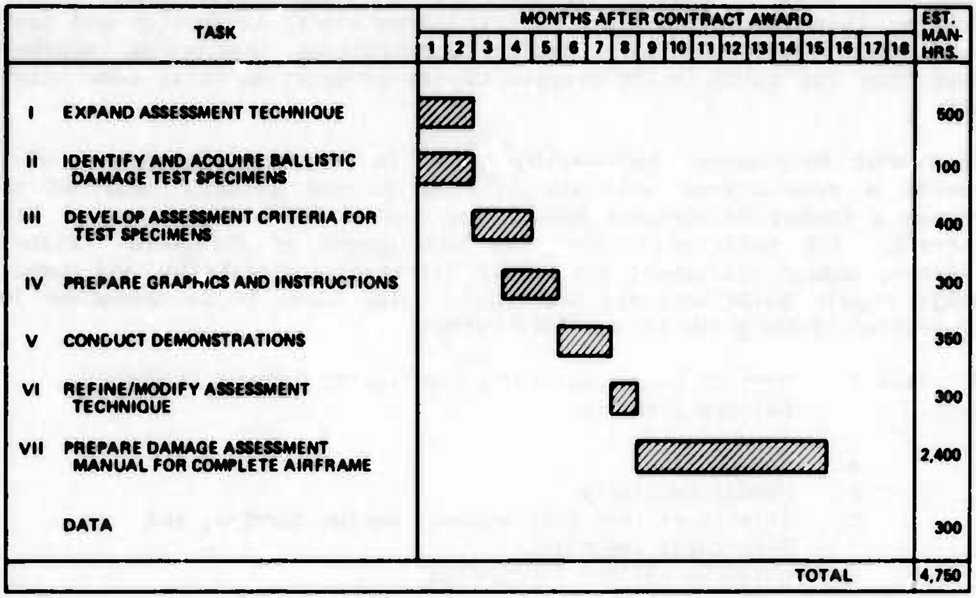


Figure 68. Preliminary Schedule and Man-Hour Estimate for a Program to Develop and Demonstrate Combat Damage Assessment Techniques

Guide be developed in two stages, the first devoted to Airframe Structures. The Stage 1 program proposed earlier will provide a fully developed and demonstrated damage assessment methodology for incorporation in the guide.

With respect to repair of combat-damaged airframe structures, the current program has explored a representative sample of interim and quick-fix approaches. The work thus far accomplished has shown that interim repair methods of this type can expedite airframe repair in combat and that such methods can provide the strength to support aircraft design loading conditions. In many cases, interim repair can restore damaged structure to original strength and stiffness. Consistent with the approach described earlier in the report, the repair schemes are generic in nature and have applications to multiple areas of the airframe.

The proposed methods employ materials, tools, and techniques which are within the existing capability of Army helicopter repairmen. The structural adequacy of repairs of this type have been demonstrated analytically with high confidence. It is felt that sufficient knowledge exists to begin developing an engineering guide for airframe combat damage repair based on this general approach. If the Army elects to develop and test highly specialized repairs for limited applications, they can be incorporated into the guide in the process of its preparation or at some later date.

The Combat Maintenance Engineering Guide for Airframe Structures will provide a manufacturer with the information and guidance required to produce a Combat Maintenance Manual for the airframe structures of his aircraft. The guide will cover the development of structural failure criteria, damage assessment and repair deferrability criteria, and combat damage repair guidelines and techniques. The tasks to be conducted in preparation of the guide are outlined below:

Task I - Develop Guidelines for Establishing Damaged Structure Failure Criteria

a. Damage Size
b. Damage Proximity
c. Effects of Load Environment, Design Margins, and Structural Redundancy
d. Go/No-Go Failure Thresholds

Task II - Develop Combat Damage Inspection Procedures

a. Damage Cleanup
b. Scope of Inspection
c. Inspection Techniques and Procedures
d. Failure Decision Criteria

Task III - Develop Guidelines for Establishing Repair Deferrability Criteria

a. Damage Limits
b. Operating Restrictions
c. Evaluation of Degraded Attributes
d. Risk Assessment

Task IV - Develop Guidelines for Establishing Combat Damage Assessment Criteria

a. Damage Scoring Criteria
b. Damage Scoring Procedures
c. Repair/Defer Decision Criteria

Task V - Develop Guidelines for Combat Damage Interim Repairs

a. Selection of Repair Materials
b. Sizing, Forming, and Fitting of Parts
c. Basic Techniques
d. External Repair Methods
e. Blind Riveting Techniques
f. Post-Repair Inspection Methods
g. Cautions and Restrictions

Task VI - Develop Guidelines for Presentation of Material in the Maintenance Manuals

a. Failure Criteria
b. Inspection Procedures
c. Repair Deferrability Criteria
d. Damage Assessment Criteria
e. Repair Techniques

Task VII - Prepare a Combat Maintenance Engineering Guide for Airframe Structures

Task I establishes engineering guidelines for the development and specification of structural failure criteria, based on damage size and location, and structural loading conditions. Policies and procedures governing field inspection of airframe combat damage are developed under Task II. In Task III, guidelines for establishing repair deferrability criteria for a helicopter airframe are developed. This includes methods of assessing degraded aircraft attributes and evaluating the risks involved with exposure to additional combat damage. Criteria for imposing aircraft operating restrictions are also established.

Task IV develops procedures that allow the aircraft manufacturer to establish combat damage assessment criteria for his aircraft. Task V provides guidance on the development and specification of combat damage repair techniques, providing generic examples which the manufacturer adapts to his particular aircraft. Task VI covers the presentation of material in Combat Maintenance Manuals, providing suggested formats and recommendations concerning the content of graphics and text. Task VII concludes the program with publication of a complete Combat Maintenance Engineering Guide for Airframe Structures.

A preliminary schedule and estimate of man-hours for a program of this scope is given in Figure 69.

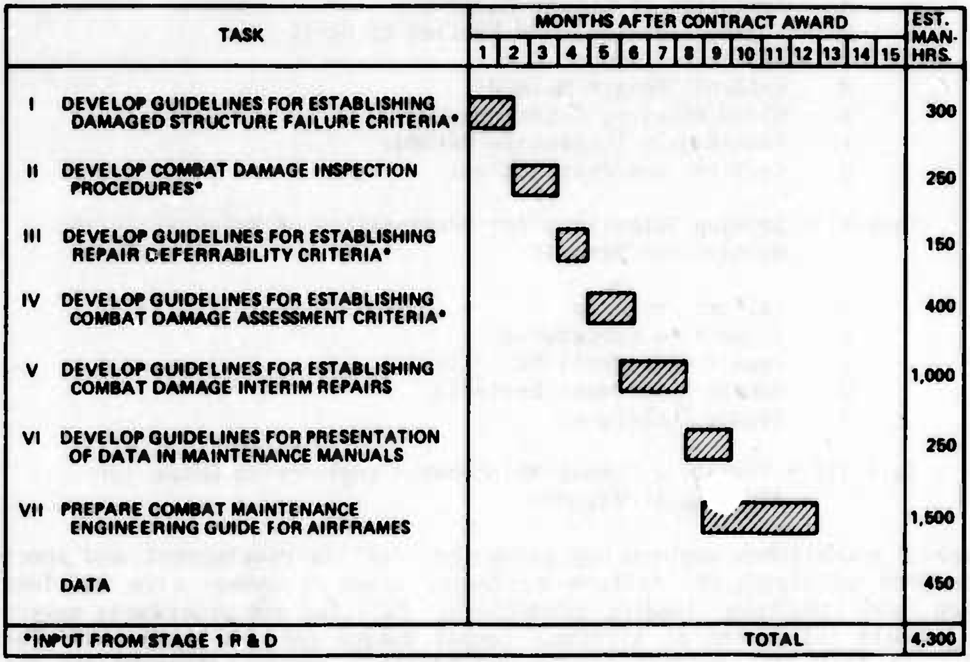


Figure 69. Preliminary Schedule and Man-Hour Estimate for a Program to Develop a Combat Maintenance Engineering Guide for Airframe Structures

STAGE 3 - MODELING AND ANALYSIS OF AIRCRAFT SYSTEMS

The current program has examined the problems of combat damage assessment and repair for one major system of the helicopter, the airframe. It is recommended that in the next phase of R&D the Army conduct an expanded analysis of aircraft combat maintenance using the modeling and analysis techniques developed in this program. The analysis should cover all systems of the aircraft with particular emphasis on systems such as electrical wiring, which may require unconventional and/or time-consuming repairs when ballistically damaged. Objectives of the program should be to assess the effects of predicted damage to the various systems of the aircraft in terms of mission capability and downtime and the potential for deferring repair and/or expediting repair of systems. Products of the analysis should include estimates of the workload that will be imposed on the various repair specialists and maintenance resources in combat, and recommendations concerning manning levels, training, serviceability criteria, maintenance procedures, and tools and equipment. Concepts for interim repair of combat-damaged systems should be investigated, together with concepts for designing aircraft systems for improved combat damage repairability. The tasks in a proposed program are outlined below:

Task I - Refine Modeling and Analysis Techniques

a. Shotline Generation
b. Shotline Modeling
c. Penetration Analysis
d. Damage Size/Effects Analysis

Task II - Conduct Modeling and Evaluate Damage Cases

a. Repairability/Deferrability
b. Mission Capability/Downtime
c. Impact on Personnel and Resources

Task III - Develop Quick-Fix/Interim Repair Concepts

a. Fluid Systems
b. Electrical Systems
c. Mechanical Systems

Task IV - Investigate Improved Combat Repairability Design Concepts

a. Current-Inventory Aircraft
b. Future Aircraft

In Task I, the modeling and analysis techniques that were used to assess the deferrability and field repairability of airframe combat damage are expanded and refined. The refinements are aimed primarily at expediting the generation of a large number of damage cases and efficiently analyzing the effects of ballistic projectile impacts on a variety of aircraft systems and components (fluid lines, wiring bundles, etc.). Improvements in the graphical projection of HEI fragment patterns and the estimation of projectile damage size are also developed.

In Task II, a large number of API and HEI damage cases are simulated, and a selection of cases involving each of the major systems of the helicopter are analyzed. Each damage case is classified with respect to the potential for deferring repair or making quick-fix field repairs in combat. The effects of system damage on mission capability and downtime are assessed together with the impact of repairs on personnel and resources.

In Task III, concepts are developed for interim repair of system combat damage that is not amenable to rapid repair via replacement of components. In Task IV, concepts for enhancing the repairability of system combat damage through improved aircraft design approaches are investigated.

A preliminary schedule and man-hour estimate for a program of this scope is given in Figure 70.

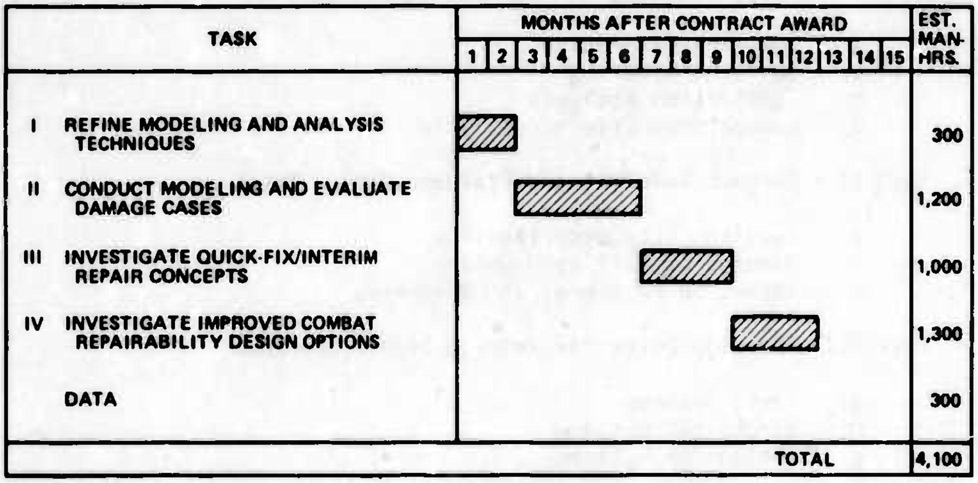


Figure 70. Preliminary Schedule and Man-Hour Estimate for a Program to Analyze Combat Damage Deferrability and Repairability for Helicopter Systems

STAGE 4 - COMBAT MAINTENANCE ENGINEERING GUIDE FOR ARMY AIRCRAFT

The final stage in the proposed sequence of R&D integrates the results of the Stage 3 program with the Combat Maintenance Engineering Guide for Airframe Structures developed in Stage 2, completing the Combat Maintenance Engineering Guide for Army Aircraft. The scope of the program needed to complete the guide will depend largely on the results of the Stage 3 program with respect to the potential for deferred repairs and interim repair of damage to helicopter systems other than the airframe structure.

REFERENCES

1. Fitzpatrick, P.R., MODEL FOR THE PREDICTION OF EXPLOSIVE PROJECTILE DAMAGE TO AIRCRAFT STRUCTURES, Report No. UTRC-76-134, United Technologies Research Center, East Hartford, CT, August 1976.

2. Ullyatt, L.G., Thompson, J.P., and Smith, L.E., TARGET DESCRIPTION FOR SURVIVABILITY/VULNERABILITY ASSESSMENT, Volume I, GEOMETRIC MODELING FOR FASTGEN (DRAFT), Falcon Research and Development Company; Report No. TR-33800, Naval Weapons Center, China Lake, CA, May 1978.

3. Belote, C.E., and Severance, J.D., FASTGEN II TARGET DESCRIPTION COMPUTER PROGRAM, Booz, Allen and Hamilton, Inc.; Report No. JTCG/AS-78-V-002, The Joint Logistics Commanders Joint Technical Coordinating Group on Aircraft Survivability, Naval Air Systems Command, Washington, DC, January 1980.

4. Burch, G.T., Jr., and Avery, J.G., AN AIRCRAFT STRUCTURAL COMBAT DAMAGE MODEL-DESIGN HANDBOOK, The Boeing Company; Report No. AFFDL-TR-70-116, Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, November 1970 (AD 877920).

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