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Advances in Engine Burst Containment and Finite Element Applications to Battle-Damaged Structure

Advisory Group for Aerospace Research & Development Paris France

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NORTH ATLANTIC TREATY ORGANIZATION

ADVISORY GROUP FOR AEROSPACE RESEARCH AND DEVELOPMENT

(ORGANISATION DU TRAITE DE L'ATLANTIQUE NORD)

AGARD Report No.648

ADVANCES IN ENGINE BURST CONTAINMENT AND

FINITE ELEMENT APPLICATIONS TO BATTLE-

DAMAGED STRUCTURE



Papers presented at the 42nd Structures and Materials Panel Meeting, Ottawa, April 1976.

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Two further papers were presented to a private session of the Working Group in April 1976. The paper by Messrs. Bristow, Davidson and Gerstle reviews some recent research into the application of fragment impact studies to an understanding of engine burst fragment impacts and the initial development of an engine burst containment system. The paper by Dr Huang described a method of analysis of a battle-damaged structure using the NASTRAN structural unalysis program supplemented by preprocessors designed to automatically generate input state: a "patching technique" is then used in the development of a finite element model truly representing a battle-damaged structure.

PREFACE

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The paper by Messrs. R.J.Bristow, C.D.Davidson and J.H.Gerstle on "Advances in Engine Burst Containment" reviews some meent research into the application of fragment impact studies to an understanding of engine burst fragment impacts and the initial development of an engine burst containment system. The paper by Dr. Pao, C Huang on "Finite Element Applications to Battle-Damaged Structure" describes a method of analysis of a battle-damaged structure using the NASTRAN structural analysis program supplemented by preprocessors designed to automatically generate input data; a "patching technique" is then used in the development of a finite element model truly representing a battle-damaged structure.

> N.F.HARPUR. Chairman, Working Group on Impact Damage folerance of Structures

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ADVANCES H: UMGINE BURST CONTAINMENT by R. J. Bristow, C. D. Davidson and J. H. Gerstle Senior Engineers P.O. Box 3999 Skattle, Washington 98124 USA

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SUMMARY

This paper prosents a partial review of recent research by The Boeing Company into the application of fragment impact studies to an understanding of engine burst fragment impacts and the initial development of an engine burst containment system using duPont Kevlar material. All tert work to date has involved translational accelerators but spin pit testing is planned for the near sture. The program has not yet resulted in a satisfactory containment system. However, it is by ped that the basic data accumulated will provide the building blocks in the development of design criteria for such a system.

In addition to a summary of program accomplishments, this paper delves into several areas where unexpected results occurred and where information was obtained that may influence future fragment containment efforts. One of these areas involves spinning fragments. None of the predicted adverse effects on Kevl- τ fabric were found. Another area concerns thermal effects. It was found that the efficiency of the barrier in stopping fragments was influenced by the temperature of the Kevlar.

INTRODUCTION

Since the early 1950's, a group at Boeing has been involved in the study of impact phenomenology and means to control the resulting damage. These studies have ranged from meteoroid protection with test velocities of up to 32,000 fps down to free-falling rocks with test velocities as low as 10 ps. During this period, many shielding concepts were developed. The usual method was to perform a number of parametric tests, describe the damage (or other parameter of interest) in terms of a mathematical model involving projectile, target, intercept and environmenta' characteristics. The resulting model was then used to optimize the shield design or to develop design cristica.

Lightweight shields sere found to require two properties: shear resistance locally around the impact point and tensile strength to bring the fragment to a stop after the initial impact. It was also noted that both tensils and shear strength requirements should be reduced by using a shield material with good elasticity. Keeping these requirements in mind, blast container weights were reduced by substituting fiberglaws fabric for the normal steel shield material. (Elasticity was increased by designing the overall container to "give" locally.) While the fiberglaws was found to be very efficient for containing blast waves and residual games, its poor bending and cut resistance made it unsuitable for containing fragments. Nylon was found to have good small fragment stepping ability, but lacked the tensile strength required to contain blast waves or large fragments.

Currently, a new fabric is $5 - \chi$ investigates. This new fabric, called "Kevlar" by its manufacturer, duPont, is receiving wide publics. If appears destined to find a number of military and commercial applications. The purpose of this paper to summarize the results of Boeing's study of the ability of Kevlar to stop fragments. Potential uses of exulting shields would be to protect explosive storage tanks, to contain itagaants from burst electrical power generating turbines in thatinary nuclear power blants, and for use as shields against the blast and fragments of HE warheads. Contain interest to AGARD would be the use of levlar shields around jet engines to contain fragments in the case of an engine burst due to battle damage. The sizes and shapes of fragments are quite variable impending on the type of engine and the failure mode. Types of disc failure modes are shown in Figure 7. Figure 2 is a photo of some of the resulting fragments.

BACKGROUND

In 1966, Boeing carried out ballistic containment tests on titanium to provide localized shielding on the Boeing 737. In 1971, tests were initiated to find a writen roving fiberglass configuration to protect a belicopter fuselage from engine blade failures. The woven roving shields were retained until the engine manufacturer rectified the blade weakness. In 1972, the acept of a lightweight flexible energy absorbing barrier utilizing a fabric was conceived. The concept was for the barrier to perform in a manner similar to a net, giving on impact and then absorbing the energy in tensile loading of the fibers. A series of ballistic impact tests was carried out on "S" glass fabric shields were inconsistent. This inconsistency was due to the suscer-ibility of the monofilament glass to handling damage and the poor cut vesistant properties of the filaments.

As a result of a material search, the duPont material Kevier was proposed since it showed good mechanical properties (Table 1). The majority of Boeing activity since has been based on Keviar material, and this paper primarily deals with work done in the containment field win this arimid fiber.

Shield Design Approach

Many ballistic barriers have been developed in the past. Nowever, these developments have generally involved solid barrier materials. By using flexible fabric materials, a number of additional variables were introduced; type of weave, fabric stretch, layer interactions, restraint of individual fibers around the barrier periphery. To investigate all of these variables in a spin pit would be economically prohibitive. For this reason, it was planned that the majority of the development work would be conducted in a ballistic impact laboratory and that development would proceed along lines established for solid harriers. In addition to economics, the ballistic lab approach had the advantages of greater control over fragment sizes, velocities and impact angles.

In the impact laboratory, the many containment shield configurations could be reduced to the best two or three which could then be spin pit tested. The spin pit would only be used to validate and confirm the laboratory results and to impart to the fragment a realistic rotational velocity.

The early shield designs were corrugated with variation in the depth and spaceing of the corrugations. A face plate of .028 CRES sheet was provided and the corrugations were held in position by wire. Flat shields were also designed of Kevlar and impact tested. The containment performance of this flat shield when based on a weight per unit area was found to be equally effective to the corrugated type shield. Since the flat shield was less costly to manufacture and, also, had installational advantages, the rewainder of the recent shield development program was based on the flat design configuration. The other variables that were investigated included varying the shield weigh? the material weave, the effects of wever tested with matrix around the Kevlar such that the barrier could replace some of the existing structure. Altogether, there were over 20 different shield design configurations.

Test Equipment

The layout of the impact test facility which is shown schematical's in Figure 3 and by photo in Figure 4 was used for the shield testing; it consisted of a 2.5 or 6 in. diameter bore launching bartel, 60 in. long, with a threaded-on breach. The projectile to be launched (Figure 5) was placed in a sabot assembly and loaded into the barrel. The impact velocity was varied by the weight and type of powder charge. The launcher muzzle extended into a plenum where the burned gases were vented and a trap was incorporated to restrain the sabot halves. As the projectile traveled downrange, it passed through two printed electrical vircuit sheets, spaced two feet apart, triggering the circuit of the electronic velocity analyzer. The impact chamber had a movable steel cover with an acrylic window to provide access for mounting of the shields and viewing ports for photography. The projectile travel from muzzle to shield was approximately 10.0 ft.

The tasidual velocity of the projectile was measured by the number of witness sheets penetrated, (Figure 6 shows witness sheets and a "flat" shield mounted on its support bracket).

A metal block was used to simulate the fragment and was varied from a 3/4 in. to 3 in. cube with variations such as changing the aspect ratio $(1 \times 1 \times 3)$ and changing its density by using different materials. The reasons for using a cube were that it has a cutting edge which would more represent engine fragments than a sphere, is easy to manufacture, and is inexpensive. It's size can be varied easily to represent different size fragments. Also, the compact shape of the cube resulted in reasonably consistent test Gata. It was the intent to impact the shield at energy levels and velocities which would be expected from an engine, e.g., no blade velocities in excess of 1200 fps and no blade root velocity greater than 900 fps.

Test Results

Figure 7 shows the containment performance of Kevlar shields for two projectile sizes, plotting shield weights (uninstalled) against contained energy. Also shown are the containment energy levels for other materials from tests done previously by other agencies and Boeing. These results reflect the flat shield configuration. It was established that the corrugated type shield and the varying types of material weave showed no advantage. A ballistic felt-faced shield showed about 5% improvement which is within the data scatter. The placing of acoustic lining material (either polvimide or aluminum) behind the shield showed no significant change in containment performance.

Empirical Hodel

Empirical and semi-empirical models have been developed in the past for many types of impact phenomena; armo: plate, structural damage, m teoroid impact, and hail to mention only a few. These models have been found to be extremely useful in designing and optimizing hardware associated with the phenomena. For this reason, an empirical model was developed to represent the laboratory containment barrier data.

The basic barrier test data was first plotted as a function of a barrier layer and witness sheet penetration as shown in Figure 8. (The witness sheets were a set of 1/15 inch aluminum plates placed behind the test barrier. Enough plates were used to assure that the cube projectile would stop somewhere in the set.) The point where the typical "5" shaped curve crosses the boundary between barrier and witness sheet penetration is the ballistic limit (incipient penetration completely through the barrier). An empirical model was then developed to express the ballistic limit as a function of several of the most important variables; fragment size, velocity, impact angle and number of layers of Kevlar. The resulting model was:

$$W = AV^2 D^{3/4} (sin \bar{v})^{5/6} - B$$

where W = areal density of Kevlar - $1b/ft^2$

- 0.067 N, N = number of K=vlar layers (9.6 oz/yd² fabric)
- V = impact velocity at ballistic limit fps
- D = cube size inches
- $\boldsymbol{\theta}$ = impact angle measured from cube flight path to barrier surface

A & B - Constants

In order to make the model more usable, the nonogram of Figure 9 was developed. Knowing the fragment size, velocity and impacting angle, the Figure 9 nonogram makes it very easy to determine the number of Kevlar layers required to stop the fragment.

Once a model such as the one above has been developed, it is useful to examine the variables in detail. The barrier weight is seen to depend on the square of the velocity of the fragment. This appears reasonable since the fragment kinetic energy depends on the square of the velocity. However, the model shows that the dependency on fragment size is only the 3/4 power of the cube dimension. This would indicate a dependence on mass of only mass to the 1/4 power. In other words, the barrier weight is not strongly dependence on fragment mass. An increase in fragment mass by a factor of 16 would require a barrier weight increase of only two.

Spinning Fragments

When an engine bursts the resulting fragments have both linear and rotational energy components. The ratio of these types of energy varies from all rotational for a complete disc to virtually all linear for a small rim fragment. It has how been felt by some investigators that the fragment spin responsible for the rotational energy would severely limit the usefulness of fabric barriers. They theorized that the rapidly spinning fragment would act like a "buzz saw" to cut through the fibers.

In order to determine if soin would indeed cause the fragment to saw through the barrier, a test series was set up in which the projectile was made to spin before hitting the barrier. This was, complished by placing a 3° wooden ramp in front of the barrier. Upon hitting the ramp, the edges of the cube projectile dug into the wood and caused the projectile to roll up the ramp. The resulting spin rate was deduced from high-speed motion pictures (normally 10,000 frames per second). Figure 10 shows the results of some of the testing. Considerable scatter is shown. However, with spir cates varying from 9000 to 24,000 RPM, o degradation in barrier efficiency was forand.

In a complete, y different type of test, some of the effects of spinning projectiles were also noted. In this test meries, the effects of projectile geometry were being studied. The cube projectiles were replaced by rods one by one by two or three unches long, fired end-way, int, the target as shown in Figure 11. This rotation was, in effect, a high speed spin by the time the rod stopped, as shown in Figure 11.

The conclusion to be drawn from these tests, and to be later verified in a spin pit, is that spin has little, if any, detrimental effect on the ability of a fabric barrier to stop fragments.

Temperature Effects

In an actual installation, the engine containment barrier will experience a range of temperatures. The effect of these variations under static conditions was known from work done by duPont (Figure 12). This work indicated that Kevlar properties were constant until a certain temperature is reached and then fall off graduals, at higher temperatures. It was decided to conduct a gest to make sure that the barrier would function properly at the highest temperature anticipated, $120^{\circ}F$. The results were surprising. Instead of getting a slightly reduced ballistic limit as expected, the Viviar material appeared to have better properties at higher temperatures. The high temperature to use were expanded and included some at cold temperatures. The results were as shown in Figure 13. Above more temperature, the ballistic limit steadily improved up to about $\approx 20^{\circ}$. Above this temperature, the efficiency of the barrier rapidly fell off.

It was surmised that the increasing ballistic limit with temperature was due to strain rate effects; that strain rate effects increased faster with temperature than the static strength decreased. In order to test this theory, a variable -pend tensile test machine was used to determine the properties of Kevlar at different temperatures. The machine was capable of strain rates from 0.05 to 18.5 in/in/min. The results are shown in Figure 14. Strain rate effects do indeed appear to be indicated.

Considerable more study is required, but it appears that the variation in ballistic limit with temperature may be used to advantage in the design of barriers. However, it appears that temperature cycling reduces the Kevlar properties in some as yet unknown manner. Figure 15 shows tests wherein test specimens were cycled various numbers of times prior to test. In all cases the capability of the barrier was reduced. As shown in the figure, few cycling data points are available, hence there is much uncertainty as to the overall effects of temperature cycling.

FUTURE PLANS

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The end objective of our work a. Boeing is to understand design criteria for a lightweight engine burst containment shield. Present effort focuses on three areas; increased energy containment, attachment design, and spin pit verification of laboratory impact testing.

The manner in which the barrier is attached to the aircraft (or to itself) is closely related to irstallation design problems. However, it is also important for the development of the barrier itself. It has been found that as the size of the fragment goes up, the greater is the dependency of the ballisti. limit on the method of attachment.

All testing to date has been with translational accelerators only. This year the plan is to verify these results in a spin pit. A disc with blades will be made to separate into three or four segments. These segments will then impact a barrier which is designed on the basis of translational tests.

CONCLUSIONS

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Progress has been made in the development of technology for engine burst containment. However, a number of major problems must be solved before a barrier of this weight can be placed in an aircraft. These problems include practical attachment concepts, temperature cycling degradation, and the extrapolation of current containment designs to the higher energy levels.



RIM SEGMENT



HUS OR SECTOR

Figure 1 Disc Failure Modes -

RIM-WER



Figure 2. Engine Burst Fragments

	TITANUUS GAL-4V	CONTINUOUS FRAMENT -S- GLASS	CONTINUOUS FILAMENT-SYNTHETIC REVLAR 20	
TENSILE STRENGTH (PSI) FRAMENT	-		449 560	
FARRIC	157,000	324,900	210,000	
WEIGHT RATIO	1 74	1.8	0 50	
LOOP STRENGTH (PSI)-FILAMENT (CUT RESISTANCE)	-	NEGLIGIOLE	240,000	
TEMPERATURE RESISTANCE (PSI)	127,806 AT 489* F	SIZING BURNS OFF ABOVE 350° F . EAVING GLASL EXPOSED AND SUBJECT TO ABRASION	FRAMENT 316,000 AT 200° F (200° F MAX FOR CONTINUOUS USE)	

Table 1. Engine Burst Containment Material Properties



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Figure 14. Temperature/Strain Rate Effects

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Figure 15. Temperature Cycling Effects

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FINITE ELEMENT APPLICATIONS TO BATTLE DAMAGED STRUCTURE

by

Dr. Pao C. Huang, Consultant Naval Surface Weapons Center White Oak Laboratory Silver Spring, Maryland 20910 United States of America

Summary

This paper introduces a "Patching Technique" for the development of a finite element model truly representing a battle-damaged aircraft. The applications of preprocessors PING and BING to the automatic generation of input data for NASTRAN analyses are also briefly shown. Finally, the importance of modeling technique is addressed.

(1) INTRODUCTION

The utilization of the finite element method in the design and analysis of a complex missile structure is an important step toward an optimized system. The great speed and precision of these techniques permit a missile to be thoroughly and repeatedly analyzed and modified, providing a more efficient weapon system. These same techniques are perfectly applicable to the structural vulnerability analysis of a hattle-damaged vehicle which, in general, has a complicated configuration and requires detailed stress and deformation data. However, the success of this computer approach depends largely on the modeling technique used to develop a (inite element model which accurately simulates the real structure.

In addition, the generation of such a model and its associated data output must be guick, economical, and routinized.

(2) FINITE ELEMENT PROCRAM - NASTRAN

NASTRAN, a general purpose finite element program for struccural analysis developed by NASA, can be used as an example of a program for which data generation can be an overwhelming task. NASTRAN is versatile and applies to a large class of static and dynamic problems as follows: ይህ በተዋቅረው የሚያስት በማስተኛው በማስተኛው በማስተኛው የሚያስት በማስተዋት የአስት በማስተኛው በማስተኛው በማስተኛው በማስተኛው በማስተኛው በማስተኛው በማስተኛው በማስተኛው በማስተኛው የሚያስት የሚያስት በማስተኛው በማስተኛው በማስተኛው የሚያስት በማስተኛው የሚያስት በማስተኛው በማስተኛው በማስተኛው በማስተኛው በማስተኛው በማስተኛው በማስተኛው በማስ

a. Static response to concentrated and distributed loads, thermal expansion, and enforced deformation

b. Dynamic response to transient loads and random excitation

c. Determination of real and complex eigenvalues for use in vibration analysis and stability analysis.

However, preparing NASTRAN input for a complicated problem is a large effort in itself. It includes the layout of a grid mesh; calculations of grid point locations; gener-tion of element properties and their connections to grid points; preparation of input sheets; and, finally, punching of input cards. All this work is extremely time consuming and requires the effort of a team or specialists. Furthermore, possible occurrences of human errors together with unavoidable redesign cycles would make the analysis formidable.

To remedy these difficulties, special input generation programs have been developed by the Naval Surface Weapons Center, White Oak Laboratory to automatically generate finite element models and their associated NASTRAN input for missile structures.

(3) PREPROCESSORS FOR NASTPAN

A Planform Input Generator (PING, [reference 1] which can rapidly develop a finite element model for an arbitrary wing planform of a missile, and a Body input Generator (BING) [reference 2] which performs the same function for any type f missile shell body are currently operational at NSWC/WOL. Utilizing these the preprocessors, a complete missile such as shown in Figure 1 can be easily and quickly generated for rigorous structural analyses. These two preprocessors contain many useful features which can be utilized to facilytate the development of a model to truly simulate a real missile.

The efficiency of PING is demonstrated in Figur' 2 where a finite element model of a double wedge, solid, sweptback wing is shown as an example. This finite element model has 277 grid points, 260 plate elements, and 1400 degrees of freedom. FING was employed in the development of this model. It only took five manhours and a few seconds of computer time to produce 1137 input cards for NASTRAN analysis.

Without PING it would take at least 360 minhours to produce the same number of cards manually. The capability of developing a finite element model rapidly and economically

is an essential requirement for such complicated work as the vulnerability study of battle damaged structures.

Figures 3 to 8 show some of the sample finite element models developed by PING and BING. Figure 3 demonstrates the useful feature of a mixed mesh which can be used to reduce the degrees of freedom in *Diss* important areas. Figure 4 shows a model of a curved delta wing. Figure 5 illustrates how patches with a circular or elliptical hole can be used with a finer mesh around the hole for more detailed stress distribution. Figure 6 shows a wing with an elliptical hole which can be developed in two stages. First, a wing model without hole is developed and the elements around the hole are removed; then a patch with the hole can be developed to fit in the opening. Figure 7 shows a complicated but realistic missile body generated by BING. It has a nose cone and a cylindrical shell with an engine howing. Figure 3 shows a finite element model of a BQM 34A wing. This built-up wing has three spars connecting two curved parels. Again, a mixed mesh is used in the wing panels to reduce the degrees of freedom without sacrificing the accuracy in the important wing root area.

Using the preprocessors and NASTRAN, reliable analytical results can now be obtained easily and rapidly. Figure 9 shows the good correlation of the theoretical and experimental data. The latter were provided by the Naval Research Laboratory from a complete vibration test of the actual missile. The theoretical results were obtained by NASTRAN on a finite element model developed by PING and BING. It only took 40 manhours to complete the vibration model and 1200 seconds of CDC 6500 computer time to obtain the first six vibration modes. With these powerful analytical tools, elaborate structural analysis certainly becomes practical in the development of a complicated missile system.

(4) PATCHING TECHNIQUE

On a demanding task such as the vulnerability study of battle damaged structures, precise stress data around the damaged area will be required to determine the possibility of crack propagation which may lead to catastrophic failure. Finite element analysis techniques will be of great value in furnishing detailed information for such a study. Therefore, an elaborate finite element model must be developed to accurately represent the damaged structure. Using PING, this task can be easily achieved. Figure 10 shows the procedure for the development of a damaged wing structure. First, a finite element model of the undamaged wing must be generated and the plate elements around the damage removed. Then patches of damaged components having smaller plate elements can be generated to fit the cutout. Finally, these patches are inserted into the proper locations to complete the finite element model for the damaged wing. This modeling procedure is designated as the "Patching Technique". The common gridpoints on the cutout boundaries are not joined by compatibility conditions but by using a common gridpoint number, therefore, no constraint equations are required. This feature not only eliminates many input data cards, but also yields a much better finite element model.

(5) ANALYSES OF BATTLE DAMAGED STRUCTURES

A damaged BQ1 34A wing was analyzed by NASTRAN under lg loading. The finite element model of the undamaged wing had 846 grid points, 849 plate elements, and 4602 degrees of freedom. This model not only too. into account the curvatures of the skin panels, but also the varying skin thickness. Five PING runs and approximately 64 manhours were taken to complete this job. The damaged wing had a slot 1.5 inches wide in the upper skin panel and extended five inches diagonally inward from the front spar to a point whele the middle spar cap was completely cut. In addition, all three spars were damaged to different degrees. Using the patching technique, the finite element model for this damaged version was quickly generated by removing elements and adding patches. The final model is shown in Figure 11. The NASTRAN analyses showed significantly higher stresses in the root area of the damaged wing than those in the corresponding region of the undamaged wing. However, the most critical point was found at the slot tip with a peak stress of 10,000 psi as indicated in the plot of iso-stress-lines. The actual damaged wing was tested to destruction, which occurred at a 3g loading. A crack was first formed at the tip of the slot then propagated toward the wing root at the resr spar. This was adequately predicted in the stress contour plot whereby a peak stress of 30000 psi was obtained at 3g level; a value which was thought to be the strength of the material at that state.

The structural response of a damaged semimonocoque fuselage was analyzed from a model by the same patching technique. A vertical slot between the second and third frames near the tail end was cut in the fuselage skin. The cut extended from the crown down to a point at 108 degrees on each side. The patch had a width covering the last three bays of the fuselage and a circumferential length longer than that of the slot. As can be seen in Figure 12, much smaller elements are used in the patch especially around the tip region where high stress concentration is anticipated. This finite element model was subsequently analyzed by NASTRAN for an 1g load condition. Proper resultant forces were placed on the four cut boundaries to transmit air pressures from the nose, wings, and tail assembly which were omitted in this truncated fuselage. Stress concentrations were found around the slot tip area with sufficient intensity such that a crack would form at this point. Catastrophic failure seems certain to occur of the acrack arresting structural member in the propagation path between frames, and the peak stress of 26000 psi shown in Figure 13 would increase rapidly as the crack enlarges.

また。 1941年の1945年のことであることのでは、東京社会の主要には、1949年の日本であるためでは、そのなどではないないでは、1947年の1947年の1947年の1947年の1947年の1947年の1947年の1947年の To demonstrate the importance of the patching technique which provides stress concentration data, another analysis was made on a model obtained simply by remiving the plate elements between the two frames to simulate the damage inflicted on the fuselage. This simple model, Figure 14, had a cutout wider than the slot but was bounded on four sides by smooth edges. NASTRAN analysis revealed much higher stresses than those of the undamaged model, however, no fanger could be detected for any catastrophic failure in this analysis. This contradictory conclusion, of course, was not totally unexpected, especially when the simple model had a structurally sound configuration. However, it did point out the danger of under-modeling and the importance of a true simulation.

The study of structural vulnerability of battle-damaged aircraft by projectile hits can be conveniently treated in two prase. In the inpact fracture phase damage criteria of instantaneous failure, i.e. the upper bound of vulnerability, are of interest. Then the assessment of local damages to the structure must be determined for subsequent survival a alyses. The prediction methods in these areas are inadequate at the present time, however, some guidelines are available for a quick estimate. In the continued flight phase where residual strength, loss of control, dynamic and aerodynamic instabilities are a concern, the finite element techniques become extremely valuable. To attack these problems two distinct finite element models should be employed. A "Static Model" with sufficient damage details can be developed for residual strength analysis while a "Kinematic Model", being much simpler than the former, can be used in the analyses of structural response. The kinematic model is definitely the cheaper one to run, yet would yield sufficiently accurate results in stiffness or dynamic analysis. For completeness, many different analyses much be performed on a large structure, these models must be carefully designed for optimization in terms of accuracy and economy.

(6) CONCLUSION

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Using the preprocessors PING and BING together with NASTRAN, finite element techniques can now be applied easily and rapidly to the study of structural vulnerability. Precise response data can be generated, analyzed for the residual strength and performance of the damaged vehicle.

Patching technique has been applied to the development of a finite element model for a damaged vehicle. The procedure is found convenient and efficient. Good stress concentration data have been obtained.

Modeling to truly represent a damaged vehicle is an important task. It should not be over- or under-designed for economical or accuracy reason.

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FIG. 1 A COMPLEY'S FINITE ELEMENT MODEL FOR ELABORATE STRUCTURAL ANALYSIS

DATA GENERATION	NA'S	TRAN	PING / NASTRAN	
BASIC PLANFORM INFORMATION	TYP AE PRESSU LCAD	RD RE	6 GRID POINTS	
I OVERALL DIMENSIONS II MESH LAYOUT	260 ELEMENTS		, ,	
IN AERO DATA				
	THRE (MAN HOUR)	NO OF Cards	TIME	NO OF CAROS
COMPUTATION	280	0	3	O
WRITE- UPS IN PROGRAM FORMATS	40	0	1	0
CAES PUNCHING	24	1137	5	29
VERIFICATION AND CORRECTION (10% EST)	16	114	5	3
INPUT CARDS REQ'D FOR NASTRAN		1137		1137
CARDS MANUALLY PUNCHED		1251		32
TOTAL TIME REQUIRED	360		5	

FIG. 2 EFFICIENCY OF PING/NASTRAN

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FIG. 3 SPARROW IN SOLID WING PLAN FORM



FIG. 4 PLANNED FINITE ELEMENT MODEL OF A CYLINDRICAL WING

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FIG. 5 SAMPLE PATCHES DEVELOPED BY PING



FIG. & WING WITH ELLIPTICAL HOLE



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FIG. 7 FUSELAGE WITH ENGINE HOUSING DEVELOPED BY BING



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FIG. 9 COMPARISON OF THE THEORTICAL AND EXPERIMENTAL DATA OF A VIBRATION MODEL DEVELOPED BY PING AND BING



MODEL FOR A DAMAGED WING WITH PING



OF THE BOM 34 A WING 1 G LDADING 2 500 PSI 3 000 PSI 4 000 PSI 5 000 PSI 5 000 PSI 5 000 PSI

ISO-STRESS-LINES FOR DAMAGED COVER

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FINITE ELEMENT MODEL OF DAMAGED BOM 34 A WING



BOM 34 A DAMAGED WING LOVER

- - CRACK DUE TO 36 LOAD





FINITE ELEMENT MODEL OF A SECTION OF A FUSELAGE

FINITE ELEMENT MODEL OF A DAMAGED FUSELAGE

DAMAGE PATCH FOR FUSELAGE

FIG. 12 DEVELOPMENT OF FINITE ELEMENT MODEL. FOR A DAMAGED FUSELAGE WITH BING



VERTICAL CU? BETWEEN FRAMES





Systortion of Damaged Area Under 1-6 LOAD condition

HIGH STRESS AT DAMAGED THP INDICATES CRITICAL CONDITION FOR CRACK PROPAGATION

FIG. 13 VULNERABILITY STUDY OF A DAMAGED MISSILE BODY



FIG. 14 DAMAGE MODEL WITH SMOOTH SIDES

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