A Methodology for Analyzing Laser-Induced Structural Damage

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Introduction

THE possibility of a weapon system incorporating a high-powered laser necessitates the development of a means for analyzing laser-induced structural damages. The problem lies in determining the degree and location of the damage. Thus, an analysis must be conducted, investigating a large number of possible levels and locations of damage. Since repeating a complete structural analysis for each hypothetical case would be extremely costly, a more cost-effective method is required.

The objective is to develop a method by which a structural designer can determine at relatively low cost those critical members of the structure needing strengthening or redundancy to survive laser strikes. We approach this task by using a finite element method and an iterative reanalysis technique applied to the damaged structure. An approximate solution to the heat conduction problem resulting from the laser engagement provides a means of evaluating the local damage. Temperatures and phase changes are translated into local structural effects such as changes in geometry, stiffness, and thermal stress. These are then translated into damage parameters consistent with the overall structural analysis.

Theory

The structural analysis method used is based on the displacement method of finite element analysis. Let $\boldsymbol{K}$ be the stiffness matrix, $\boldsymbol{D}$ the displacement vector, and $\boldsymbol{P}$ the total structural load matrix. Then the problem reduces[1] to

$$\boldsymbol{KD}=\boldsymbol{P} \tag{1}$$

a set of algebraic equations that may be solved numerically.

Most of the computational time is expended on the decomposition of the stiffness matrix. As decomposition is independent of the loads or the number of separate loading conditions, an analysis using multiple loading conditions requires only a single decomposition. To further reduce the cost of analysis so that a comprehensive analysis can be performed, a reanalysis method has been developed.[2]

Assume now that Eq.(1) has been solved for $\boldsymbol{D}$. When the structure is damaged, the equilibrium equation changes to

$$\boldsymbol{K}^*\boldsymbol{D}^*=\boldsymbol{P} \tag{2}$$

where $\boldsymbol{K}^*$ is the stiffness matrix and $\boldsymbol{D}^*$ is the response for the damaged case. Let $\boldsymbol{D}^*$ be written in terms of a truncated Taylor series expansion,

$$\boldsymbol{D}^*=\boldsymbol{D}+\delta\boldsymbol{D}=\boldsymbol{D}+\sum_{j=1}^{n}\frac{\partial \boldsymbol{D}}{\partial g_i}\mathrm{d}g_i \tag{3}$$

where g_i are n implicit parameters whose changes will affect the displacement. If the stiffness is assumed linear in g_i, the loads independent of g_i, Eq. 3 and the original equilibrium equation can be manipulated to

$$\boldsymbol{K}\delta\boldsymbol{D}=-\delta\boldsymbol{K}(\boldsymbol{D}+\delta\boldsymbol{D}) \tag{4}$$

An iterative algorithm for the perturbation can be written as

$$\delta\boldsymbol{D}^{q+1}=-\boldsymbol{K}^{-1}\delta\boldsymbol{K}(\boldsymbol{D}+\delta\boldsymbol{D}^{q}) \tag{5}$$

where q is the cycle of iteration.

The solution converges if $[\boldsymbol{I}+\boldsymbol{\phi}+\boldsymbol{\phi}^2+\ldots+\boldsymbol{\phi}^q]$ converges, where $\boldsymbol{\phi}=-\boldsymbol{K}^{-1}\delta\boldsymbol{K}$. For small changes in structural stiffness, $\phi^q\to 0\to\infty$, and the solution converges.

Convergence alone is not a justification for using an iterative technique. To be useful, the technique must be more efficient than direct analysis of the modified or damaged structure. Simulation of a laser strike on a flat panel modeled with 48 triangular elements produced the estimate that the run time for approximately 30 cycles of iteration is equivalent to the time required for one direct analysis of the damaged structure.

The laser-induced effects to be included are the loss of structure due to melting, the induced thermal stresses resulting from thermal expansion, and the change in material properties due to temperature changes. In order to evaluate these effects, the temperature changes in the structure must first be determined. We consider only an axially symmetric, continuous, and stationary laser beam striking a flat plate at normal incidence. An approximate temperature distribution is obtained by dividing the panel into finite cells and performing heat balances on each at successive increments in time, as previously described.[3,4]

With the heating of elements, thermal expansion occurs and generates thermal stresses. With the addition of the thermal load, Eq. 1 becomes

$$\boldsymbol{KD}=\boldsymbol{P}+\boldsymbol{\psi}=\boldsymbol{P}^* \tag{6}$$

where ψ contains the thermal load effects determined from the change in temperature. Note that solutions for various thermal loads require only a single decomposition of $\boldsymbol{K}$.

The damage due to material loss is incorporated by determining the loss of stiffness an individual element incurs when

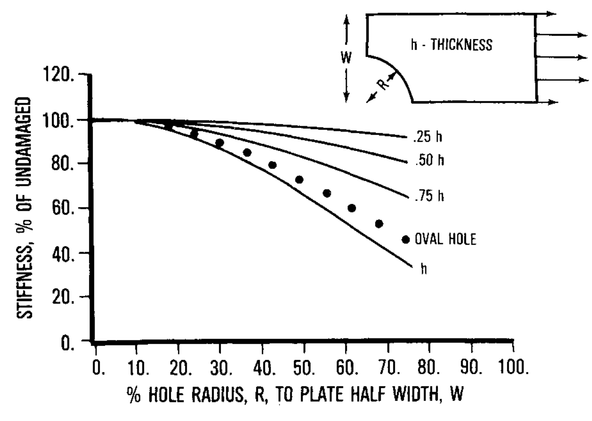

Fig. 1 Residual stiffness of plates with holes of varying depths and radius.

Received July 14, 1984; presented as Paper 84-2521 at the AIAA/AHS/ASEE Aircraft Design, Systems and Operations Meeting, San Diego, CA, Oct. 31-Nov. 2, 1984; Engineering Note submitted Aug. 26, 1985. This paper is declared a work of the U.S. Government and therefore is in the public domain.

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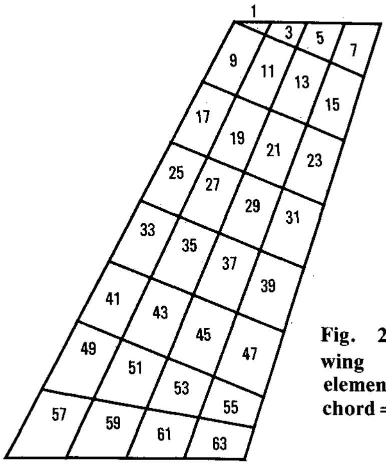

Fig. 2 Intermediate complexity wing model (even-numbered elements on lower surface); root chord = 48 in., semispan = 90 in.

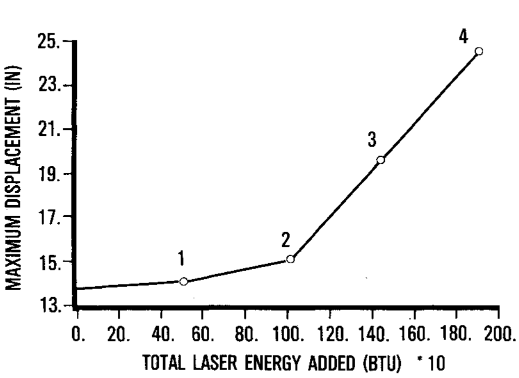

Fig. 3 Effect of laser energy absorbed on the maximum tip displacement.

some of its material is removed by melting. A parametric study was conducted with a finite element analysis of a flat panel in a state of tension with holes of varying diameters and depths. In Fig. 1, hole depths are expressed as fractions of panel thickness. The oval hole has an aspect ratio of 2, is completely through the panel, and is aligned with the long axis transverse to the load. The stiffness for the damaged panel was calculated as a percentage of the stiffness for the undamaged panel. The results are used to determine the loss of stiffness of an individual element. Repeating this for each affected element enables the δK due to loss of structure to be determined.

Although the major loss of stiffness to an element would usually be due to a loss of material caused by melting, the effect on the entire structure need not be significant unless the melt occurred on a major load-carrying member. However, a temperature rise can occur over a larger section of the structure and reduce Young's modulus in a number of elements, resulting in a major stiffness change for the entire structure. This effect was evaluated by assigning to each element a modulus corresponding to an average temperature, determined by taking the mean of the nodal temperatures. A table of Young's modulus temperature was developed for T2014 aluminum[5] and used to compute a new Young's modulus for each element and the resulting δK.

Example

The laser damage program developed was applied to two different structures. These structures are of two levels of complexity, one being a simple two-dimensional plate and the other a much more refined three-dimensional wing structure. These problems demonstrate the ability of the program to be used for a smaller localized analysis as well as for a large aircraft structure.

The three-dimensional structure analyzed was the "intermediate-complexity wing" shown in planform in Fig. 2. It is a typical wing box structure clamped at the root and modeled using rods, triangular membranes, quadrilateral membranes, and shear panels.[2] The model employed 88 nodes and 158 elements. The top and bottom skins are modeled using triangular and quadrilateral membranes and the spars and ribs by shear panels with rods providing the axial support. The material in the panel is assumed to be 0.1 in. aluminum. The applied loading condition was generated by using simplified pressure distributions representative of a subsonic forward-center-of pressure loading. This cantilevered wing was chosen for study as an illustration of the application of the method to the preliminary design of a lifting surface.

The damage cases for this structure were constructed by varying the locations and the duration times of the laser strikes. A beam radius of 4.0 in. and an absorbed peak intensity of $F_0 = 25$ Btu/in.^{2}/s. was assumed. The laser damage simulated represents that caused by a beam moving across the wing at approximately center span. All three damage modes were included. The overall objective was to observe the response of the structure as the damage increased to the level at which the structure would collapse. The various cases and results are listed in Table 1. The temperatures were determined as described previously, using eight elements through the thickness with a radial dimension of 0.197 in. The beam was considered to move across the wing, completely melting each element in the times given. After the temperatures were found, new element stiffnesses were determined, taking into account the material removed and the changes in modulus. The iterative finite element analysis, incorporating the thermal load, was then used to determine displacements. The number of iterations required to achieve convergence is given. Each of these four cases was also analyzed by NASTRAN to obtain

Table 1 Description of intermediate complexity wing cases

Case	Elements exposed	Element volume removed through melt, %	Exposure endurance, s	Max disp, in.	Iteration time as % of undamaged solution time	Iteration cycles	Damage range
1	27	100	.455	14.11	15.00	4	Minor
2	27	100	.455	15.12	42.67	15	Medium
	29	100	.455				
3	25	100	.455	19.52	200.00	80	Major
	27	100	.44				
	29	100	.40				
4	25	100	.40	24.54	360.00	150	Major
	27	100	.44				
	29	100	.44				
	31	63.49	.44				

confirmation that convergence occurred. A more complete discussion of results is given in Refs. 6 and 7.

Because the overall structure is large enough that the temperature changes are localized, major damage to an element (such as complete removal through melt) generates only a localized damage condition and a minor change to the total structure. For example, in case 1, element 27 was entirely removed by damage, yet the displacement at the wing tip increased by only 2.3% from the undamaged response. Case 4 represents a laser beam moving across the wing at approximately center span, resulting in a hole cut through the top surface for 93.75% of the chord at that spanwise location. This is the collapse condition; the prescribed load is now an ultimate load for the damaged structure.

Figure 3 reflects the results of all four cases. In this figure, the total laser energy added is plotted against the maximum displacement for each case. The plot indicates that an energy threshold exists, above which the damage level increases significantly. The value of that threshold is, of course, specific to the conditions of the engagement, the nature of the material, and the details of the structure.

Although not discussed here, the time required to apply this reanalysis technique was compared with that required to generate a model for each case. A substantial reduction in the number of man-hours required to produce models for multiple damage levels was found.[6]

The reanalysis method for laser damage calculations was found to be capable of predicting the response of a structure under load subjected to a laser strike. Given the numerous assumptions, any numerical values computed by this process should be treated as only tentative, but adequate for the conceptual design phase. The findings indicate that for most minor and medium ranges of damage, the reanalysis technique is an efficient method for analyzing a large number of damage possibilities.

References

[1]Cook, R.D., *Concepts and Applications of Finite Element Analysis*, 2nd ed., John Wiley and Sons, Inc., New York, 1974.

[2]Venkayya, V.B., Khot, N.S., and Eastep, F.E., "Vulnerability Analysis of Optimized Structures," *AIAA Journal*, Vol. 16, Nov. 1978, pp. 1189-1195.

[3]Torvik, P.J., *A Numerical Procedure for Two Dimensional Heating and Melting Calculations with Applications to Laser Effects*, AFIT TR 72-2, March 1972.

[4]Torvik, P.J., "Prediction of Melt-through Times for Laser Heating," *AIAA Journal*, Vol. 14, April 1976, pp. 417-418; see also AIAA Paper 75-114, Jan. 1975.

[5]*Military Standardization Handbook: Metallic Materials and Elements for Aerospace Vehicle Structures*, Vol. 1, U.S. Department of Defense, 1978.

[6]Bryan, S.K., *Reanalysis Methods for Structures with Laser Induced Damage*, M.S. Thesis, Air Force Institute of Technology, Wright-Patterson Air Force Base, OH, March 1983.

[7]Bryan, S.L, Torvik, P.J., and Venkayya, V.B., "A Methodology for Analyzing Laser Induced Structural Damage," AIAA Paper 84-2521, Nov. 1984.