FINITE ELEMENT ANALYSIS OF HELICOPTER STRUCTURES

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SUMMARY

This paper presents the progress at Sikorsky Aircraft of the applications of finite element (F.E.) analysis for helicopter structures. The finite element analysis is now the standard method for helicopter airframe structures, and the use is now being expanded for 3D analysis of mechanical components. Examples of application are presented for airframe, mechanical components, and composite structure. Data are presented on the increase of model size, computer usage, and the effect on reducing stress analysis costs. Future applications for the use of finite element analysis for helicopter structures are projected.

INTRODUCTION

Prior to 1971 the major method for analysis of helicopter structures at Sikorsky Aircraft was the usual strength-of-materials approach. Semiempirical corrections were made to account for complex cutouts or stress concentration regions. Elastic energy methods were employed to a limited degree for some redundant structural areas, but mainly as a stress check for highly stressed parts. In the 1960's, an airframe was extensively strain gaged (about a thousand gages were used) to correlate stress analysis with test results. This correlation study showed that an appreciable weight reduction could be achieved if a more accurate analysis method was used to predict internal load paths. As a result a force method was used to reanalyze the airframe type structures, and appreciably improved correlation was obtained. However, the principal problem was the inability to use such improved methods to effect the structural design in a timely manner.

A review in 1970 indicated that the finite element technology had progressed to a level that this methodology could be employed as a design tool for helicopter airframes. The most promising features were that, with moderate instruction, the design stress engineer would be able to employ finite element analysis, and the more accurate analysis could be employed in the design iteration schedule. The expected results would be reduction in structural weight, with less risk of major design changes arising from not meeting final test verification. Table I illustrates the major milestones in the use of finite element technology at Sikorsky Aircraft.

A survey was made as to which of the many well developed finite element programs to use. NASTRAN® was selected since it met the selecting criteria (i.e., user oriented, analysis features, and, most important, the projected continued support for updating and development). The next step was to check out the use of NASTRAN to predict stresses and deflections. A static test airframe of the CH-53A helicopter was used and the test correlation was found to be highly superior to previous stress methods used. As a result, the confidence and experience was gained to employ the finite element technology to the subsequent airframes listed in Table I.

The first full finite element analysis was for the BLACK HAWK prototype airframe. Structural weight was reduced about ten percent and the accuracy was confirmed by subsequent airframe static tests. The same finite element technology was employed for the RSRA (rotor systems research aircraft), CH-53E (super stallion), and the S-76 commercial airframes.

The finite element analysis is now being employed for helicopter mechanical components. However, most of the mechanical components require a 3D finite element analysis to account for rapid changes in geometry as well as for accurate stress predictions. The availability of mesh generators has made 3D finite element analysis practical, and correlation of stress predictions has been within 10 percent accuracy for highly stressed regions.

This paper will present the progress of finite element technology, applications, benefits derived, and projection of future applications.

APPLICATIONS

The applications presented represent some of the typical structures where finite element analysis is important for helicopters.

As previously mentioned, finite element analysis was first started with the airframe structures. The BLACK HAWK helicopter shown in Figure 1 is typical of the complexity of helicopter airframes.

The airframe has large openings for troop entry on both sides, numerous openings for windows and the main rotor transmission support. Thus the center cabin has many structural discontinuities, for which the usual strength-of-materials approach would be questionable to predict accurate internal load distributions. In addition to the many usual flight and ground load conditions, the BLACK HAWK airframe was designed to meet the Army requirements for crashworthiness.

The finite element model of the BLACK HAWK is shown in Figure 2. The entire airframe, the vertical and horizontal tail surfaces, and the effect of the main rotor transmission were included in the finite element analysis with a resultant 9000 degrees of freedom. The use of finite element technology contributed significantly to a highly efficient airframe.

Another important area of helicopter applications is the design of mechanical components. These are usually of complex shape and designed for cyclic loadings. Fatigue testing is usually required to verify the component design. The goal is to "must pass" the fatigue requirements at the first test evaluation. Failure to do so involves costly changes and significant problems in schedule. Thus finite element technology, with its inherent improvement in stress prediction, is well warranted for use with helicopter mechanical components. Due to the complexity of shapes, a 3D analysis is required to achieve the accuracies desired. The 3D model shown in Figure 3 represents a segment of the CH-53A/D helicopter swashplate. By using cyclic symmetry, only the segment shown was required for the analysis, but even this segment represents 5500 degrees of freedom (equivalent to the center cabin required of the BLACK HAWK). The 3D finite element analysis provided stress results within ten percent of static test data in the highly stressed regions.

Another area of application is with the use of advanced composite materials. Sikorsky Aircraft is rapidly utilizing these advanced materials for primary structures. Since the composites are essentially linear elastic in the fiber dominated orientations, little or no plastic relief is obtained at stress concentration regions. The example shown in Figure 4 represents the finite element model of a composite bolted joint. With metal joints, the usual assumption is that bolt loads will redistribute due to local yielding. However, for composite materials, it is essential to account for accurate load distribution and concentrated stresses at the bolt regions. The finite element model shown in Figure 4 is made very fine at the bolt locations to obtain accurate local loadings for a subsequent laminate stress analysis.

ASSESSMENT OF FINITE ELEMENT ANALYSIS

The accuracy of the finite element methods as used at Sikorsky Aircraft has been well proven with the correlations obtained for airframe and mechanical components. Developments will include reduced computer time, use of improved elements, and reduced schedule time with interactive modeling.

The increasing size of the model is beginning to become a problem. As shown in Figure 5, the general number of degrees of freedom (D.O.F.) was maintained at the 5000 number level for a long period. As more of the structure is analyzed, the size grows rapidly. A 9000 D.O.F. model has been used for the production version of the BLACK HAWK fuselage. Substructuring will help in reducing some of the work load. However, 3D analysis, even on the swashplate segment, has already reached the 5000 D.O.F. level and can be expected to grow rapidly, perhaps to levels of 20,000 in the next few years. Improvements in interactive modeling, substructuring, and others will be required to handle models of this size.

Computer time is now becoming an appreciable cost factor. Figure 6 illustrates the rapid rise in total CPU time in the past five years. CPU time can be expected to rise even more rapidly in the next decade. It would appear that the finite element work load is increasing to a level which requires fully dedicated, higher speed computers.

The question arises as to what benefits the finite element technology has brought forth. First of all the increased accuracy is estimated to have resulted in a 5 to 10 percent reduction in the weight of airframe structures. We can expect even greater reductions in the weight of helicopter mechanical components when the technology is employed to the same degree as for airframe structures.

Most important is the effect on the engineering costs to analyze structures. A best estimate of the savings in engineering hours is illustrated in Figure 7. One measure is the number of hours for stress analysis per square foot of structure. In 1977 it took only one sixth the stress hours per square foot used in 1962 for airframe structures. Thus, the engineering cost effectiveness appears to be more than ample to trade off against increased computer charges.

FUTURE APPLICATIONS OF FINITE ELEMENT ANALYSIS

We can expect increased usage of finite element analysis for weight reduction, reducing engineering costs for analysis of complex structures, and the probable reduction of development costs for helicopter components. In addition, the complexity of 3D anisotropic composite structures will require the use of finite element methods because of the inability to accurately analyze by simpler strength-of-materials methods.

The damage tolerant aspect of structural design will require the use of fracture mechanics and will be integrated with finite element methods. It will be necessary to have such a combination to enable rapid design iteration and arrive at design solutions rather than completely relying on the static or fatigue test evaluation to make design changes.

Another area of application will be to permit rapid design iteration using interactive modeling. The goal would be to permit on-the-spot stress analysis and design changes to arrive at an optimum design. This goal is a long range objective and may be reached as the finite technology is improved and the capability of the computer is increased.

CONCLUDING REMARKS

Finite element analysis is now established as the standard method for helicopter airframe analysis and is now required by the military services. Figure 8 illustrates the many Sikorsky airframe applications.

It is expected that the 3D finite element analysis will soon be a standard requirement for mechanical components, and the technology is progressing in this area.

Finite element analysis will be a requirement for primary advanced composite components because of the need to account for the complex layups and anisotropic behavior of these materials. The increasing model size from fuller use of finite element analysis and the 3D applications will put further requirements on efficient modeling and increased computer capabilities.

We can also expect further finite element applications to be required for damage tolerant design and optimization of the helicopter structures.

TABLE I - FINITE ELEMENT MILESTONES SHOW INCREASING APPLICATIONS

. Survey Selected NASTRAN	1971
. Test Correlation on Airframe	1972
. First Full Application, BLACK HAWK Prototype	1973
. RSRA Airframe	1974
. First Application to Mechanical Components	1974
. CH-53E (Super Stallion) Airframe	1975
. Canopy and Airframe	1976
. Commercial S-76 Airframe	1976
. First 3D Analysis and Correlation	1976
. Production BLACK HAWK Airframe	1977

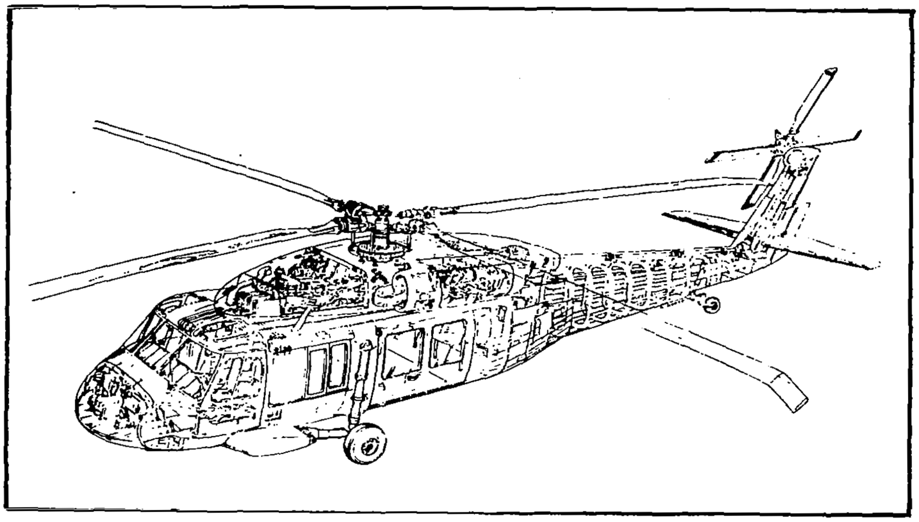

Figure 1.- Finite element technology provided highly efficient BLACK HAWK airframe.

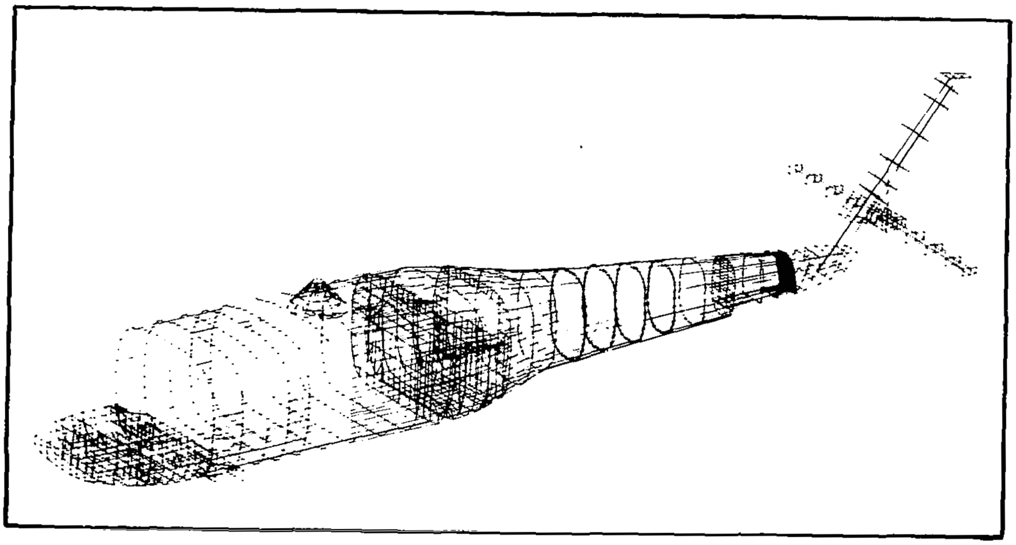

Figure 2.- Finite element model of BLACK HAWK.

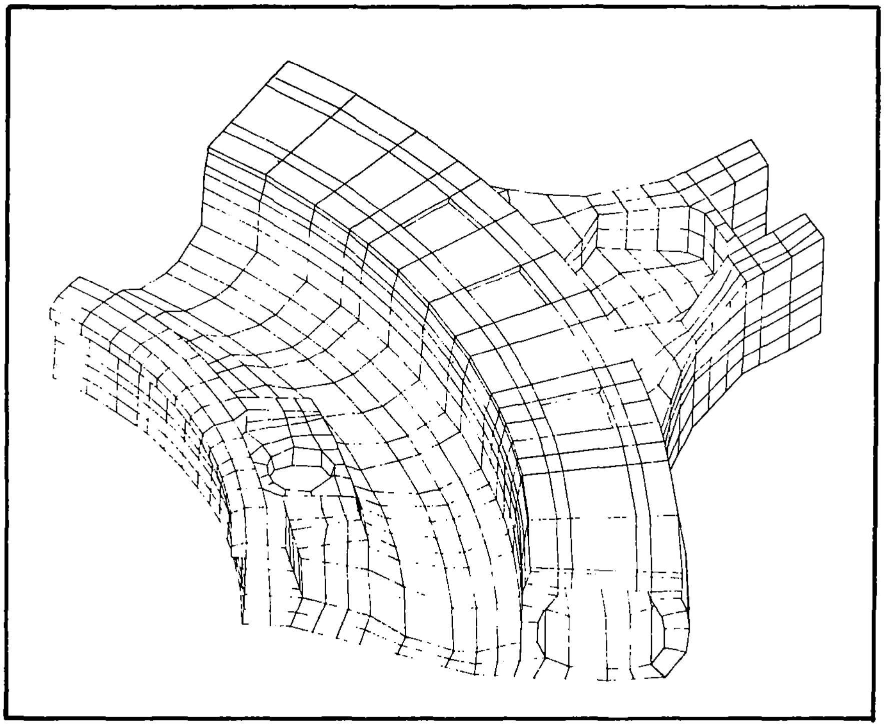

Figure 3.- NASTRAN 3D model CH-53A/D rotating swashplate.

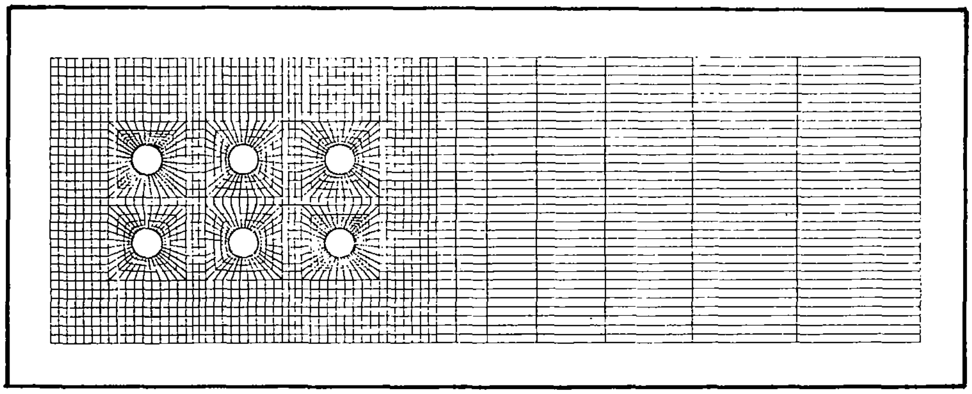

Figure 4.- Finite element analysis of composite materials bolted joint.

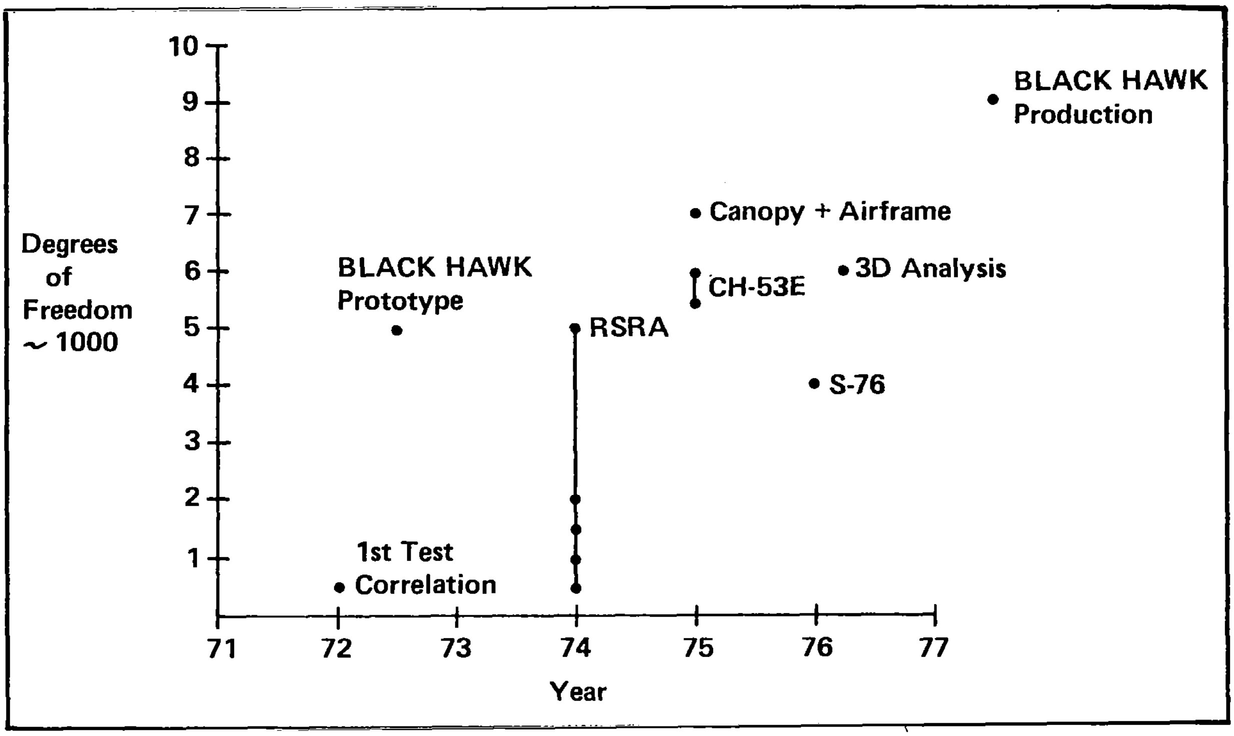

Figure 5.- Model size is increasing.

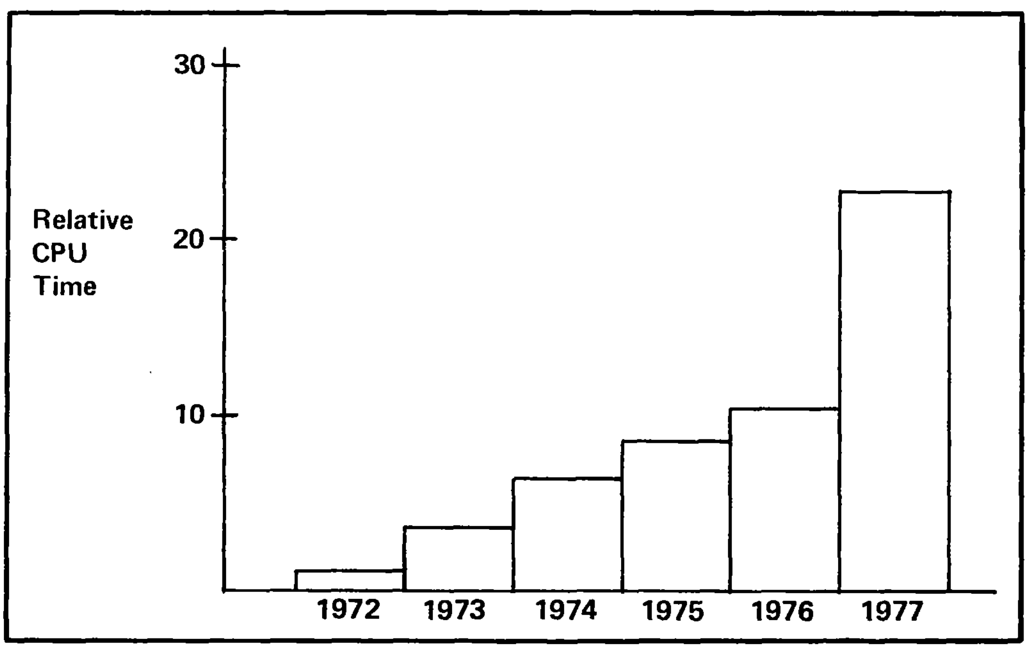

Figure 6.- Computer usage steadily increases.

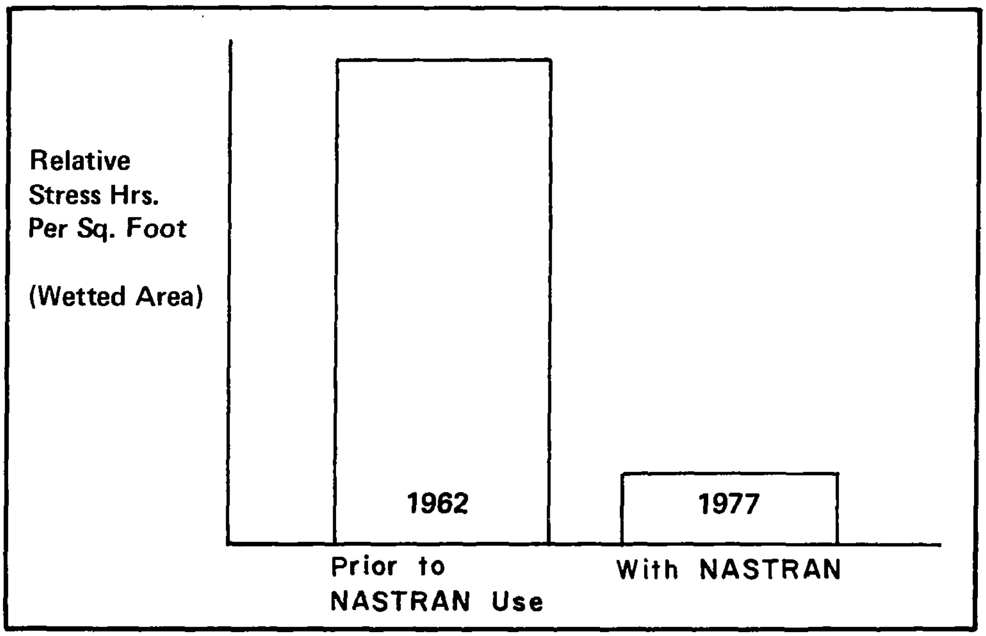

Figure 7.- NASTRAN has reduced stress hours by a factor of 6.

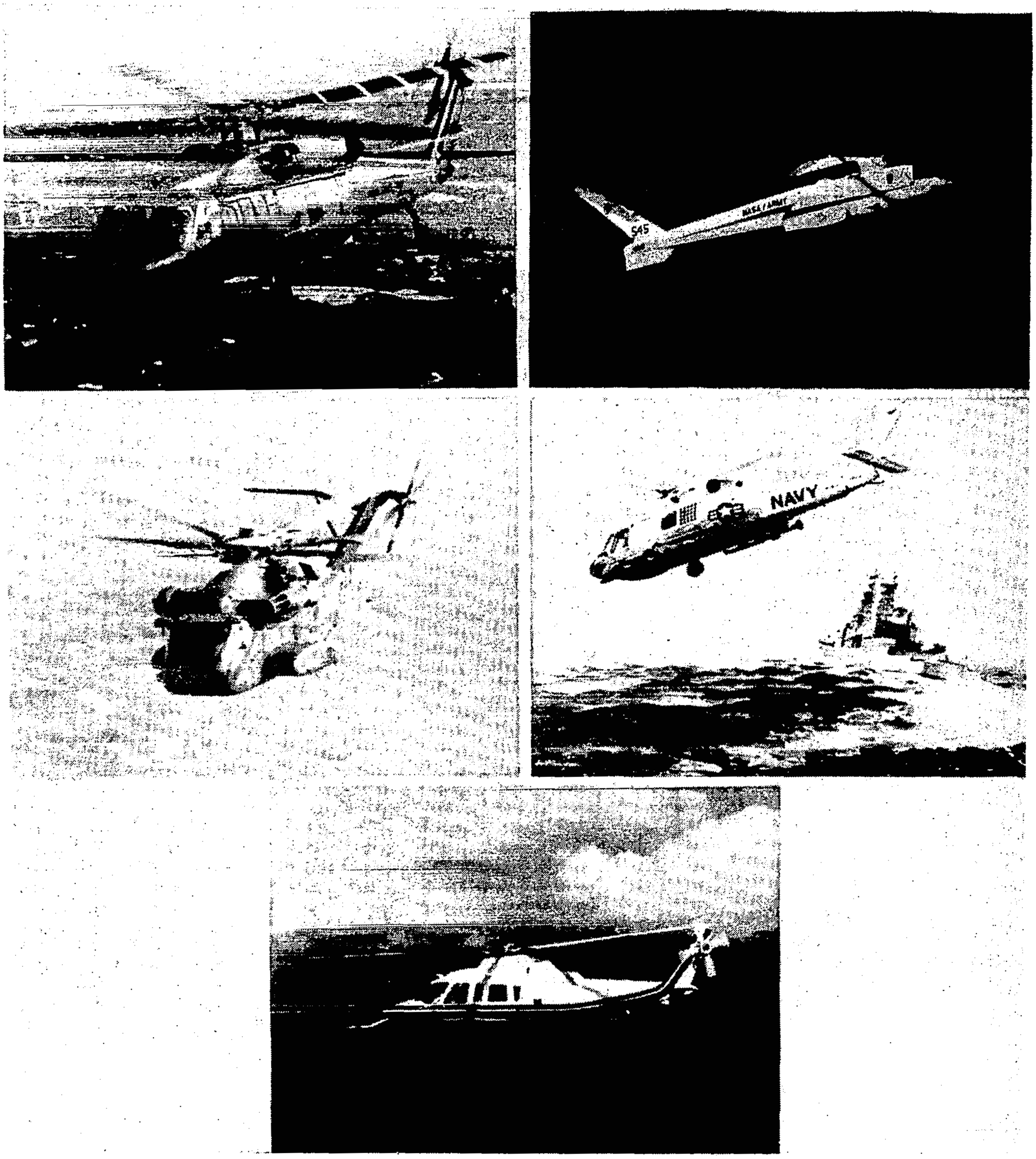

Figure 8.- Finite element analysis now established as standard for helicopter structures.