ICAS-86-3.1.3

AUTOMATED STRUCTURAL OPTIMISATION AT WARTON

R.I.KERR, Head of Structural Analysis
and
D. THOMPSON, Principal Stress Engineer
British Aerospace PLC,
Military Aircraft Division,
Warton Aerodrome.
Preston, Lancashire PR4 1AX

ABSTRACT

Several years ago a program (based on the constant energy density concept) for the design of minimum weight structures was produced by the Warton Division of BAe. This program immediately proved its worth by the reductions in cost and improvements in quality resulting from its use and thus it became an accepted part of the design process.

However, it soon became obvious that the "engineering" required to convert the idealised optimum into a practical structure could often cause the loss of much of the weight reduction achieved by the basic optimisation. Thus development of the program aimed at producing more practical solutions was undertaken. These developments were naturally tailored to meet the requirements of the types of structure designed by this division.

Although this development process is still far from complete, it is our opinion that the advantage to be gained by concentrating on this practical aspect of the problem outweighs that offered by the use more esoteric numerical optimisation algorithms.

The bulk of the paper is devoted to the presentation of examples of the use of the program in its current form. A brief description of some of the developments proposed for the future is also given.

I INTRODUCTION

In the past aircraft structures were designed to meet strength criteria. These were traditionally satisfied by the so-called "Constant Stress" solution in which each element of the structure is loaded to its maximum under at least one loading case.

For a statically determinate structure the application of this principle is obviously a simple matter whereas redundant structures obviously require an "analyse-redesign-redesign" iterative approach. Fortunately for most practical structures this approach converges rapidly.

Thus, the main problem was the solution of highly redundant structures. This was solved by the advent of high-speed digital computers and the development, particularly during the '50s and '60s, of finite element methods based initially on the force method and latterly concentrating on the displacement method.

Apart from a certain amount of work aimed at improved elements and solution algorithms the pace of work on the development of automated structural analysis/design slowed somewhat since the last major problem posed by the current generation of aircraft (as recognised by the current generation of stress engineers) appeared to be solved.

However, the advent of aircraft whose structures are designed largely by stiffness requirements and the introduction of new materials such as carbon fibre soon ended this hiatus.

Although a little earlier work had been carried out in an attempt to find analytical methods for the design of minimum weight structures designed by stiffness criteria (see for instance reference 1) it was not until the vast increases in the capacity and speed of computers which occurred in the '70s (and are still continuing) that automated design, as opposed to analysis, became a serious possibility.

Energy based optimality criteria for the solution of the stiffness based problem were developed simultaneously by various companies on both sides of the Atlantic, amongst these being the Warton Division of the British Aircraft Corporation, as it was then known (see references 2 and 3). As with the constant stress solutions the simple iterative approach shown in fig. 1 was found to converge rapidly for most practical structures (as opposed to the well documented "difficult" examples).

These initial efforts to solve the design problem have been gradually extended over the years to produce the current Warton programme "ECLIPSE". Each stage of this development has been a response to problems arising during the normal work of the design offices.

Thus, the present status of the program is described in this paper together with descriptions of typical examples of its use. A brief description of some of the proposed future extensions is also included.

II THE CURRENT CAPABILITY OF ECLIPSE

The medium term development of ECLIPSE has been aimed at the production of a method to derive practical solutions to practical design problems arising during the normal business of this division. The cost of each stage of this work has been justified in the short term by gradual improvements to the capability of the design offices.

Thus the direction taken by this development has been dependant on the hardware currently available in this division rather than relying on the acquisition of increased orders of computing power planned for some years hence.

As a result of this constraint the approach to overall strength design has been restricted to the single constant stress solution. However much useful development has been achieved in the following areas.

1. Additional Stiffness Based Criteria
The simple optimality criterion described in the appendix is applicable only to generalised displacement constraints for structures with fixed loading. Criteria of this type are relatively rare in the design of aircraft structures which are usually required to satisfy complex performance requirements when acted on by loads which vary appreciably as the structure deflects.

However it can be shown that if the form of the energy is suitably modified the basic form of the theorem may still be used.

It is worthy of note that the relevant energy forms are never experienced by the actual structure and that the use of these energies in the program results in significant decreases in the resulting structure weight.

As a result of this area of development the program is now capable of dealing with the following practical types of criteria.

a) Generalised Displacement
b) Aero. Efficiency
c) Roll Rate
d) Divergence Speed
e) Natural Frequency
f) Frequency Separation
g) Flutter Speed

2. Local Strength Requirements
Apart from overall strength requirements imposed by maximum allowable stress and/or strain the final structure must satisfy a variety of detail stressing requirements.

If these are not included in the optimisation program then much of the advantage achieved by the use of that method may be lost during the subsequent "engineering". Indeed these post-optimisation modifications may result in a failure to meet the original criteria, especially where these were stiffness based. Thus many of the routines from the in-house automated detail stressing system (ADS) have been included in the optimisation programme. These include the following:-

a) Local panel buckling
b) Local panel pressures (aerodynamic, fuel etd.)
c) Brazier Loads

Multi-directional C/F panels which require to be stiffened are treated by a local optimisation routine to select the fibre directions to be reinforced.

3. General
Apart from the above specific areas, a variety of developments have been included in order to increase the scope of the method and the practicability of the solutions generated. Amongst these are the following:-

a) Minimum Sizes. This is intended to cover manufacturing restrictions etc.
b) Fixed Sizes, enabling redesign to be restricted to specified areas of the structure
c) Coupled Sizes. This facility allows structures manufactured from sheet material to be treated.
d) Coordinate Modification. This is important for structures such as thin wings where the panel thicknesses are often appreciable proportions of the total structure depth. Thus the out-of-plane coordinates can be automatically modified so that the nodes remain at the centre of the panel thickness.
e) Multiple Sets of Fixations
This enables symmetric and antisymmetric (and hence asymmetric) criterion to be considered within a single optimisation of half a symmetric structure
f) Limits to the proportion of fibres in a single direction in a multi-directional C/F panel.
g) Integral number of fibres.

III EXAMPLES OF THE USE OF ECLIPSE

The sizing of structures designed by stiffness criteria (particularly those incorporating C/F construction) by a method based on "Inspired" guesswork can be extremely laborious. To overcome this problem ECLIPSE was developed and in this it has proved extremely successful as is demonstrated by the coarse mesh example shown in figure 2.

This represents a wing mounted on flexible fuselage frames which is required to satisfy 8 strength criteria and 3 stiffness criteria (frequency separation sub and super-sonic roll rates) out of balance wing loads are reacted by shears around the frames. The distribution (but not the magnitude) of this shear round each individual frame was pre-specified. Convergence was achieved after 3 or 4 analysis cycles as is demonstrated in table 1 and the computer time involved in the re-sizing routines was negligible when compared with the time spent in NASTRAN.

However, as the development of the program has progressed, it has proved its value in a variety of other spheres. Amongst these are the following:-

1) Preliminary sizing of structures prior to analysis.
Much of the time involved in setting up a FEM analysis of a new structure is spent on the manual estimation of the element sizes. It is the practice at Warton to input only minimum sizes and let ECLIPSE compute more representative values. A typical example of this approach was the fuselage illustrated in figure 3.

The total computing cost of under £200 was obviously much less than that which would have been required by the alternative manual sizing.

2) Weight estimation
The standard weight estimation formulae in current use have limitations, particularly for structures made of C/F and/or designed by stiffness criteria. Thus ECLIPSE is often used to make more realistic estimates.

3) Parametric studies
The efficiency of the method enables it to be used for carrying out parametric studies at the project stage (a purpose for which the weight prediction formulae mentioned above are certainly not adequate). Thus studies on the effects of altering numbers of spars and/or ribs, normal versus swept spars, basic fibre direction etc. are routinely carried out using this method.

4) Topological Optimisation
If every feasible spar and/or rib is introduced into a wing optimisation, unwanted elements will remain at minimum sizes. This approach has been used to find the optimum layout.

5) Check Stressing
The inclusion of increasing numbers of detail stressing routines into the program affords a simple method of check stressing existing structures.

As a result of this variety of use, ECLIPSE has made its contribution to every major (and several minor) structural component of each aircraft (or project) designed at Warton for at least the last decade.

IV FUTURE EXTENSIONS

As a result of the environment in which ECLIPSE was developed the current programme has capabilities uniquely tailored to the solution of problems posed by the types of aircraft designed at Warton. However this method does have drawbacks compared with a more formally planned approach.

Thus, much of the current development is aimed at producing a "productionised" version of the programme. Obviously running ECLIPSE requires an appreciable amount of data extra to that needed by a simple NASTRAN analysis. Thus, input forms similar to NASTRAN data have been devised for this and are currently being incorporated into ECLIPSE together with improved graphics.

In addition to this a variety of extra facilities are currently under development. Amongst these are the following:-

1) Thickness Gradients
It should be possible to limit the rate at which the thicknesses of C/F panels change. This maximum rate of change may well be of the order of 1:200 and obviously infers a variable interdependence between the thicknesses of adjacent panels.

2) Buckling of Spar Webs
Because optimisations are often carried out on coarse grids an idealised spar may represent n spars of the real structure, where n>1. Thus, if t is the thickness of such a web carrying a shear load S. Then a web of thickness t/n must not buckle at a load of less than S/n.

3) Skin-Stringer Design
Routines are to be included to compute the optimum stringer to stabilise skins.

4) Bearing Stresses
In addition to the normal strength resizing based on principal and maximum shear stresses, a facility to include bearing limitations is also required.

APPENDIX 1 THE OPTIMALITY THEOREM

It can be shown that, for any element j of a minimum weight structure satisfying a stiffness based design criteria:-

$$\frac{n_j}{W_j} \sum_{i=1}^{m} C_i E_{ij} = 1$$

where W_j = weight of element j
E_{ij} = energy of element j corresponding to criterion i
C_i = constant (i.e. independant of j)
and the stiffness of element j is proportional to W_j raised to the power n_j.

Thus, by the application of this theorem the problem is changed from the search for the individual element weights to the search for the m values of C_i, often a reduction of several orders.

List of References

Ref
1. A.K. Berry and R.I.Kerr, "Minimum Weight of a Swept Back Wing Spar Designed by Stiffness Criteria", Sir W.G. Armstrong Whitworth Aircraft Ltd., Research Report R.185, December 1952.

2. R.A.Gellatly, "Survey of the State-of-the-Art of Optimisation Technology within NATO Countries", Second Symposium on Structural Optimisation, AGARD Conf. Proceed. NO. 123, April 1973.

3. I.C. Taig and R.I.Kerr, "Optimisation of Aircraft Structures with Multiple Stiffness Requirements", Second Symposium on Structural Optimisation, AGARD Conf. Proceed. NO. 123, April 1973.

ACKNOWLEDGEMENT

The Authors wish to thank British Aerospace for permission to publish this paper.

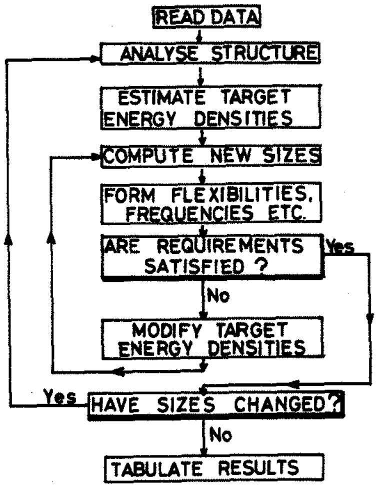


FIG 1 OPTIMISATION FLOW-CHART

STIFFNESS OPTIMISATION HISTORY

K_1 Sub-sonic Roll Rate.

K_2 Super-sonic Roll Rate.

K_3 Frequency Separation.

$\bar{K}_i$ Achieved Value K_i Target Value

Itn No.	$\frac{\bar{K}_1}{K_1}$	$\frac{\bar{K}_2}{K_2}$	$\frac{\bar{K}_3}{K_3}$	W_{Total}
0	0.988	0.959	0.602	332.8
1	1.107	1.110	0.855	344.1
2	1.100	1.073	0.960	340.6
3	1.051	0.993	0.973	338.4
4	1.075	1.014	1.008	338.3

TABLE 1

406 NODES, 1471 ELEMENTS,

8 Strength Criteria

3 Stiffness Criteria

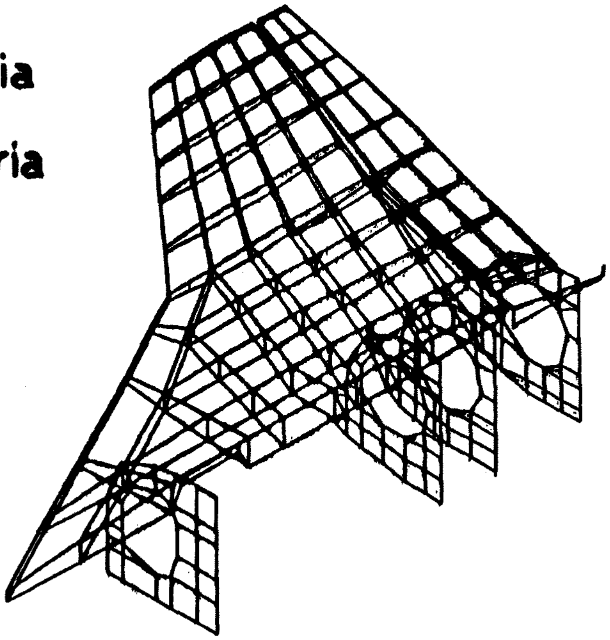
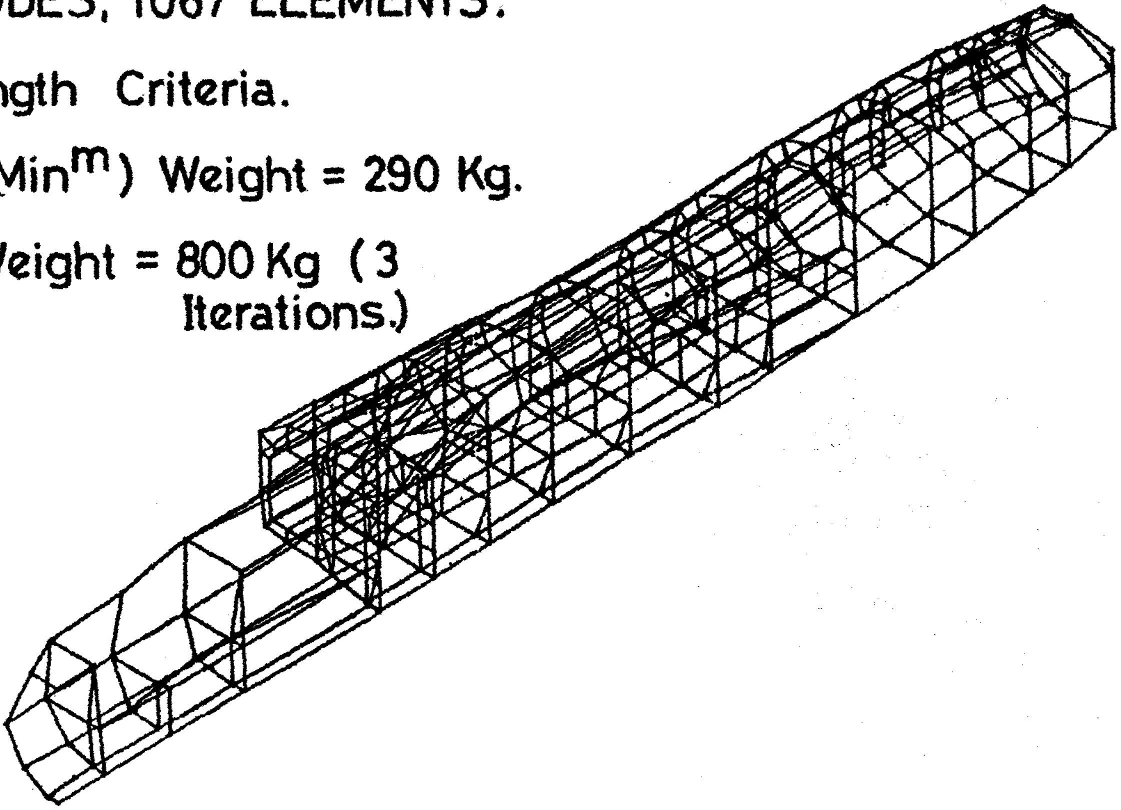


FIG. 2



344 NODES, 1067 ELEMENTS.

2 Strength Criteria.

Initial (Min^{m}) Weight = 290 Kg.

Final Weight = 800 Kg (3 Iterations.)

FIG. 3