SPECIAL-PURPOSE PROGRAMS FOR STRUCTURAL DESIGN AND OPTIMIZATION

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Abstract

When a design problem can be described in a general enough way, special-purpose programs can relieve the designer of much repetitive work and leave him free to concentrate on essential aspects of the design. Such programs for a wing cross-section, for laminate optimization, and for a fuselage cut-out are discussed in this paper. The first two of these use mainly the conventional engineering formulae; the third uses a finite element calculation coupled with a sensitivity analysis for "what-if" studies. In all cases a structural analysis can be followed by optimization of the design. Considerable attention in the development of the programs is given to ensuring that the user remains in control of the design as it proceeds, by suitable choice of constraints placed on it and by other means. The programs allow parameter variation, user-defined constraints on variables such as stringer pitch and minimum thickness, discrete layer thickness for a composite laminate, standard sections for stringers, and simple modification of a design as it is refined. Use of these programs is an effective method to explore a design problem, to determine the most significant design parameters, and to arrive at a feasible and efficient design.

Introduction

The development of some special-purpose programs for different aspects of structural design is discussed in this paper. Various phases in the structural design process can be recognized, following the initial concept of a design:

- a preliminary design phase, characterised by a multi-disciplinary approach to the design problem, in which aerodynamics and performance, structural design and aeroelasticity, and other aspects are all involved in the design process. At the conclusion of this phase the external form of the aircraft is largely settled.
- a structural design phase, in which alternative forms of structure are investigated, the layout of main structural members and internal load distribution are largely determined, and a global optimization may have been performed.
- a detail design phase, in which a further sizing of the structure takes place, including some degree of optimization of the detail design of the shell structure, local reinforcements, and joint design.

Progress in the development of a structural design module as part of a multi-disciplinary design package has been described in a previous ICAS paper [1]. The design programs discussed in the present paper all relate to the second and third phases in design referred to above. Two of these programs, one for a wing cross-section and one for a composite laminate or sandwich panel, are for the personal computer. These form part of a more extensive set of what are intended to be readily accessible, user-friendly design programs, currently under development. The third program discussed is for the reinforcement around a cut-out for a door in a pressurized fuselage. This uses a finite element analysis with extensive computer graphics, requiring therefore a graphics work station. Much of the program development in this case can be incorporated into a "toolbox" of computer routines, available for a far wider range of design problems. Emphasis is given here to the functionality of the programs, and to the philosophy behind them, rather than to specific information about the use of the programs. This information is available in the various User's Guides [2][3][4].

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The programs are meant to serve as a direct aid to the designer, saving much repetitive work, enabling a wider range of designs to be explored, and allowing parametric variations and "what-if" studies to be performed at an early stage of a design. In all the programs a chosen design can be analysed, and its performance assessed. Optimization procedures are employed to search for an improved solution to the design problem, while allowing the designer the freedom to "steer" the design by suitable choice of constraints imposed on it. Considerable attention is given in the development of the programs to ensuring that the user remains in control of the design as it proceeds, that any changes considered necessary can easily be introduced, and that the user is aware of the effect of all constraints placed on the design. The development of such programs also requires a precisely defined design methodology and can, therefore, encourage development of the design process itself.

Program for a Wing Cross-section

For some commonly occurring problems in aircraft design, the layout of the structure can be described in a general enough way to apply to a wide range of designs, and at the same time the usual engineering formulae are adequate for much of the structural analysis. An automated design procedure can then be both quick and highly effective. Examples of such problems are the design of a wing and fuselage cross-section. Here only the first of these will be discussed further. The external shape depends on the chosen wing profile. Internally, the structural form is typically a thin shell, reinforced by stringers, and supported by longitudinal spars and transverse ribs. Design freedom is primarily the thickness of skins, spar webs and ribs, and the design of stringers, stiffeners and possibly other reinforcing members. The conventional design procedure is an iterative process, in which the margins of safety are progressively brought to the same level in different failure modes under the specified loading cases. Specific design parameters such stringer pitch are chosen on the basis of experience, coupled with manufacturing requirements. Parametric studies are commonly performed to search for an efficient design. However, if an automated design procedure can be coupled to an optimization routine, this can assist in finding a feasible solution as well as directing the solution to a minimum weight design.

The program WingDesign has been developed for the design of a wing cross-section [5]. The generic form of structure (the torsion box of the wing) is shown in figure 1. To reduce the number of design variables, standardized shapes of stringer are used (corresponding to those used in practice) and restrictions are placed on the number of different skin thicknesses. Upper and lower bounds can be placed on sheet thickness, stringer area and stringer pitch. Material data, including allowable stresses for static strength or fatigue, are supplied by the user, or may be read from an existing file. The loading is defined by various combinations of shear force, bending moment and twisting moment on the cross-section. The analysis performed by the program includes the stress distribution in the cross-section, buckling of skins panels and spar webs,

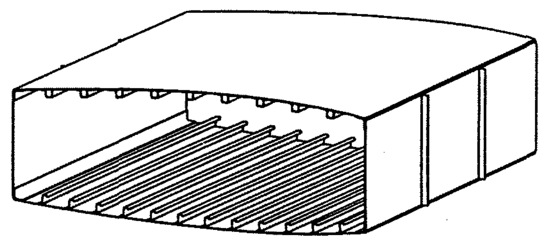


Figure 1. Generic form of torsion box structure.

torsional and flexural stiffness, and the mass of the structure. If selected, a post-buckling analysis for the skin panels takes account of the reduction in stiffness of the buckled skin. For the spar webs, a post-buckling analysis includes the maximum stress in the web and failure of the stiffeners, using standard diagonal-tension theory. Optimization takes place by a two-level procedure. At the upper level a direct search method is used to determine optimum skin and spar web thicknesses, with minimum torsional stiffness as constraint. At the lower level individual skin and spar panels are optimized by suitable choice of stringer or stiffener pitch and dimensions, with fixed skin and web thicknesses. Program output includes minimum margins of safety in the most critical load cases, actual and allowable stresses, flexural and torsional stiffness, for either an existing or an optimized design, and in the latter case the new dimensions of the structure.

As already indicated, an essential requirement for a design program of this kind is that the designer can control the design at every stage, and be able to adapt it as necessary. The following means are available to achieve an effective control over the design:

- active/non-active design variables may be selected as required, e.g. fixed stringer pitch to suit adjacent panels
- upper/lower limits may be set to limit geometric variations, e.g. minimum skin thickness for rivets or other attachments
- various stringer/stiffener types may be selected, e.g. Z-section, hat-section
- appropriate constraints may be selected, depending on the application e.g. post-buckling spar webs/non-buckling wing skins
- analysis option permits "what-if" studies, e.g. effect of some specified change in stringer pitch or dimension (or change in some combination of these) on stresses in the structure
- optimization option permits "optimum sensitivity" studies, e.g. effect of some change in design (such as stringer pitch) on the weight of the structure when both the "before" and "after" situations are optimized designs.

In a typical design session using WingDesign, the external shape of the wing cross-section is read from the data base of a CAD-system, or may be input by the user in terms of coordinate values. Spar positions are also located. The geometry is completed by choosing appropriate stringers and stiffeners for the skins and spar webs, respectively, and by defining certain other aspects of the geometry. A graphical interface for this purpose has been developed (see figure 2 - this actually applies to an earlier version of the program; a new version of the interface is planned). Load cases are input by the user, together with material data. An initial design can

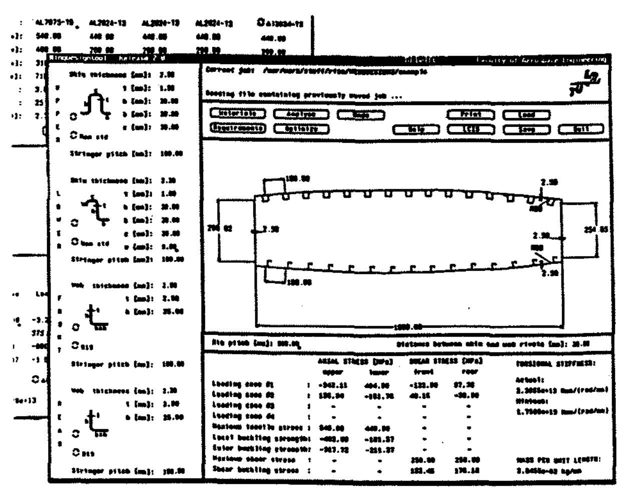


Figure 2. Graphical interface for WingDesign.

be analysed, and the design assessed. Before proceeding to optimization it is desirable to check that sensible decisions have been made with regard to limits such as minimum stringer pitch, choice of active constraints, materials and so on, to ensure that a usable initial design has been defined. Editing of data relating to the design is readily done through a menu system in the newest version of the program. Following a first optimization, upper and lower limits on dimensions may be changed as required for a practical design, thicknesses set to available sheet thicknesses and these variables made inactive, and the optimization repeated with the previous design as starting point. The effect of constraints such as minimum stringer pitch or given rib pitch is readily explored by simply changing these values and repeating the optimization. Figure 3 shows the effect of a limitation on stringer pitch on the mass per metre length of the torsion box, in a specific example.

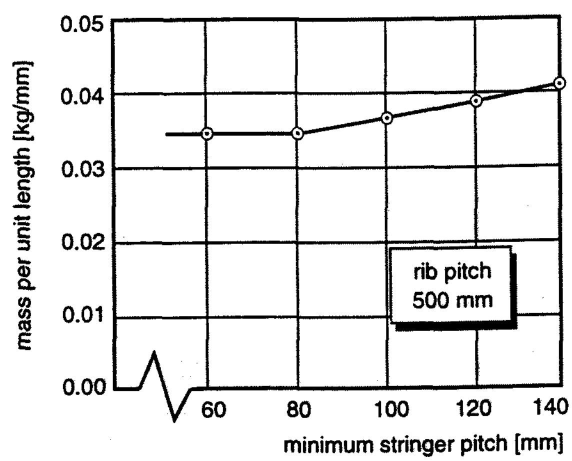


Figure 3. Effect of minimum stringer pitch on mass of torsion box.

Below a certain minimum stringer pitch there is no effect, because the optimum stringer pitch is in any case greater than the given minimum. Above this minimum stringer pitch the effect is nevertheless quite small, showing the effectiveness of the optimization procedure in adjusting other dimensions to compensate for this constraint.

The further development of these detail design programs will be into an integrated, more versatile package AeSOpS (Aerospace Structural Optimization System) in which specific analysis routines used in the design can also be accessed. The programs are at present restricted to metal structures, for which suitable crack growth and damage tolerance routines are to be incorporated. The program SaPanO, described in the following section, is being used in the first stage of the extension of the programs to composite structures. Appropriate routines for the design of ribs and frames are also being developed. These improvements have to be accompanied by a more powerful optimization procedure. The proposed organization for the further development of AeSOpS is shown in figure 4.

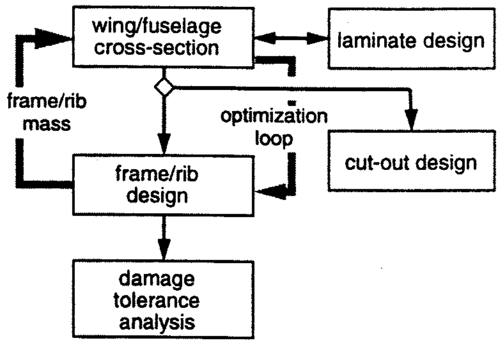


Figure 4. Further development of AeSOpS.

Program for Laminate Optimization

The freedom in design offered by the use of composites, whether in conventional laminates or in sandwich panels, makes use of optimization techniques a natural choice as an aid to the designer. Classical laminate theory is a well established and reliable basis for the analysis of composite laminates. Various additions to the theory, in particular with regard to transverse shear flexibility, significantly extend its range of usefulness so that it can also be applied to composite sandwich panels. For an effective optimization it is necessary to define the laminate (or sandwich panel) in a sufficiently general way to not unduly restrict the designer's freedom, while maintaining a practical lay-up complying with discrete ply thickness and other restrictions. Commonly occurring design requirements are defined which cover many practical situations and yet are amenable to rather rapid analysis, as is essential in an optimization procedure which is inherently iterative in nature. With this philosophy the computer program SaPanO (SAndwich PANel Optimization) has been developed to provide a fast and easy to use program for the design of both composite laminates and sandwich panels[6]. Use of this program gives good insight into the design problem, also when restrictions such as discrete ply thickness and other lay-up restrictions have to be taken into account.

Figure 5 illustrates the type of sandwich panel that can be designed using SaPanO. When the core is omitted the panel becomes a conventional composite laminate. The panel can be loaded under any combination of in-plane tension, compression and shear. When these loads are applied other than on the neutral plane, such as for a sandwich panel crimped at the edges and with one face kept flat, out-of-plane bending of the panel is taken into account. The laminate itself is defined layer by layer, as a number of plies n_i, of given material comprising the layer i ($i = 1,...N$) at some angle of orientation θ_i and in given sequence. This implies some restriction on design freedom when N is not very large but, as compared with defining the laminate ply by ply, significantly reduces the number of design variables in the optimization. Not only n_i but also θ_i are treated, for convenience, as discrete variables. The core of a sandwich panel is treated simply as an additional layer. Ply properties (and the properties of the sandwich core, if present) may be chosen from a set of standard materials held in a data file, or can be supplied by the user.

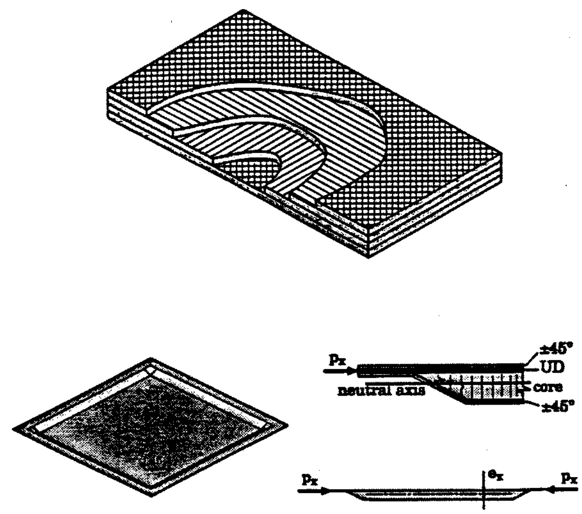


Figure 5. Typical form of sandwich panel in SaPanO

Analysis of the laminate or sandwich panel includes the strain in the panel, the stresses in the individual layers, panel buckling, as well as wrinkling of the faces in the case of a sandwich panel. Classical laminate theory is used to analyse the stress in each layer, and the overall strain. Buckling analysis, also wrinkling, is based as far as possible on standard engineering formulae. In some cases, for example buckling in shear for which no simple theoretical formulae are available, empirical formulae are fitted to the results of a numerical analysis, since it would take too long to perform this numerical analysis "live" each time it is required during optimization. Corrections are introduced to allow for transverse shear flexibility, and to take into account the individual bending stiffness of the faces of a sandwich panel. A method based on cylindrical bending is used to eliminate the coupled in-plane and bending stiffness matrix of a non-symmetrical lay-up (the so-called "*B*-matrix"). Under eccentric loading, the buckling analysis is replaced by a beam-column type of analysis. In this case panel deflection is expressed in a double Fourier series, and the bending stress in each layer is added to the direct effect of the in-plane loading.

Any or all of the constraints referred to above may be selected by the designer. A minimum number of plies in each layer may be specified, as well as a maximum total thickness. Use of these limits, together with appropriate selection of constraints and the initial choice of lay-up, give the user considerable freedom in designing the laminate. A user friendly interface makes it straightforward to make changes to some given design and perform a new analysis. However, the optimization routine provided is an effective means of reaching a satisfactory design, i.e. one of minimum weight satisfying all constraints. The optimization routine is the Complex method, modified to account for discrete variables [7]. In brief, this begins with a randomly generated set of feasible designs, which are sorted to find the worst design. This one is rejected and a new design added to the set by "reflection" of the design point corresponding to the rejected design through the centroid of the design points of the whole set (it being assumed that here is more likely to be a good design). The constraints must be satisfied at all stages in this procedure, and in addition all design variables take only their permitted discrete values. Figure 6 illustrates this procedure.

In practice the program can be used in different ways. An initial design can be analysed and its performance matched against the requirements. Making whatever changes are considered necessary, the design can be re-analysed, and so on. However, more effective is to allow the optimization routine to perform this re-sizing, still taking account of discrete ply thickness. With appropriately chosen constraints and a limited number of layers, the design will still largely conform to the initial design. If a larger number of

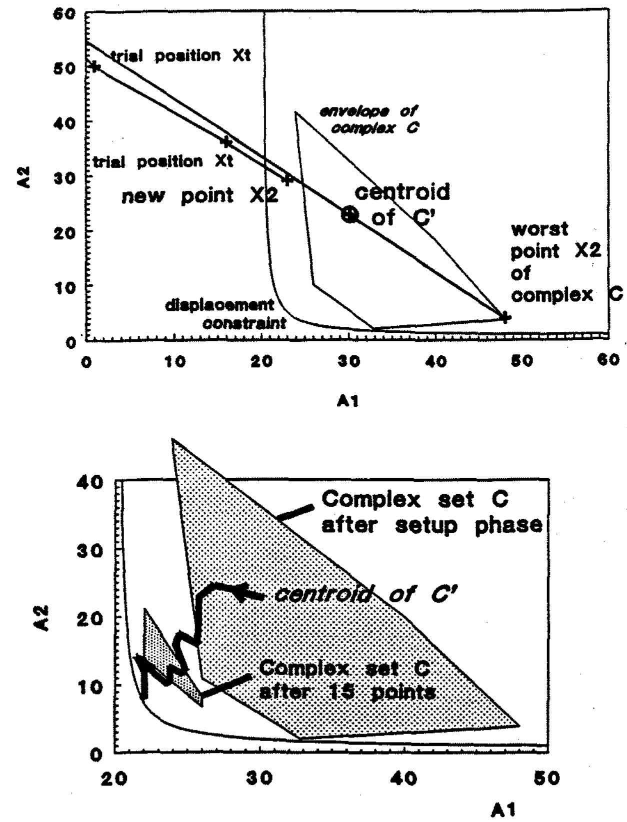


Figure 6. Discrete variable optimization by the Complex method.

layers is permitted, with more variety in ply orientation, the optimization routine can select what is in effect a new design. This may still be modified to some degree to suit the designer's wishes, for example to allow a proper lay-up to accommodate fasteners, or for improved resistance to impact damage. Should it be found that, say, for a sandwich panel the total thickness is too great, this constraint may be set to some chosen maximum thickness and the optimization repeated. Optimization can be performed for several loading cases, i.e. alternative loads for the same design. This is a valuable feature not only because a purely intuitive design process becomes much more difficult in this situation, but also because frequently no one loading case is dominant. The optimization procedure is then able to find the best compromise, in which different layers in the laminate become critical under different load cases, or perhaps in which different buckling modes correspond to different load cases.

Practical limitations on ply thickness can have a considerable effect on total laminate thickness, especially at low load levels. The chosen optimization routine is effective in taking discrete

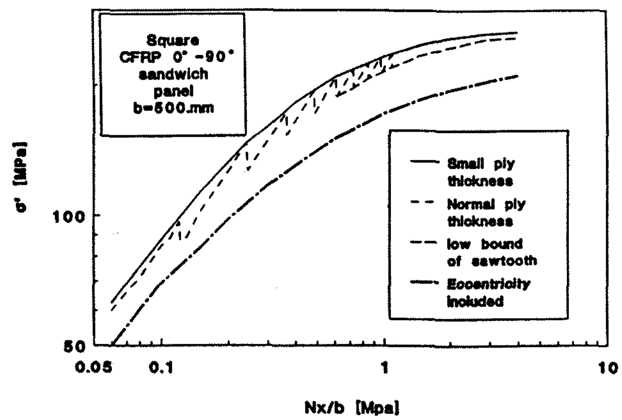
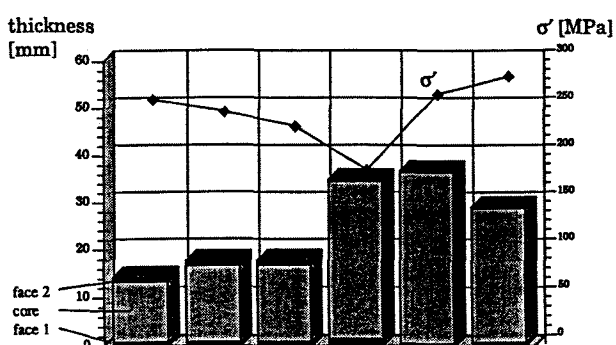


Figure 7. Efficiency of optimized sandwich panels.

ply thickness into account. Figure 7 shows the efficiency of a certain sandwich panel - actually equivalent stress σ' based on the face material plotted against structural index N_x/b, where N_x is the uniaxial compressive loading and b is the dimension of the square panel. The "sawteeth" in this graph, when one whole ply is added to a face, are as small as they are because of the compromise reached with other design variables (in this case total thickness of the sandwich panel) during optimization. The same graph also shows the significant effect of eccentricity, when the load is applied in one face of the sandwich panel. Figure 8 compares the design of some square sandwich panels (N_x = -500 N/mm, b = 500 mm) in different situations. The "realistic" panel in this figure is permitted +/-45° plies in addition to the 0/90° plies in the other panels. The significant effect of eccentrically applied load is again seen in this figure.



Case	no transverse shear	continuous thickness	discrete thickness	discrete thickness	UD face (not in Table 21)	realistic panel
face layup	0°-90°	0°-90°	0°-90°	0°-90°	0°	realistic
eccentricity	no	no	no	yes	yes	yes

Figure 8. Comparison of sandwich panels under different conditions.

Finite Element Based Design Procedure

While for the type of problem in the previous two sections use of the conventional engineering formulae was satisfactory, for a more detailed analysis and in any case for more complex structures such as the wing-fuselage connection or the reinforcement around a cut-out for a fuselage door a finite element analysis is called for. Although this has become the standard method for structures of complex shape, its use in design is somewhat more problematic. Obstacles to the efficient use of the finite element method in a design procedure can be identified as follows:

- generation and up-dating of the finite element model
- the iterative character of the design process
- lack of insight into the design problem offered by a finite element analysis.

With regard to the first of these, generation of the finite element model, this is not only initial geometry definition and meshing but also verification of the model and, where necessary, mesh refinement. This process can demand considerable engineering time, as does the subsequent modification of the finite element model as the design progresses; this may involve not only changes in element properties such as thickness but also geometric changes and subsequent re-meshing. A user-friendly geometry definition and an automatic (re-)meshing procedure can help to alleviate this difficulty.

With regard to the iterative character of the design process, it is of course possible to perform an iterative procedure in which the structure is re-analysed a number of times, the structure being increased or decreased in thickness (or other dimension) at each step according to the stress in that part. Convergence of this re-sizing process is usually slow since there is in general no unique relationship between the stress in some part of the structure and the dimension of that part. Furthermore this procedure does not necessarily lead to an optimum, mostly producing an adequate structure (i.e. one with the required minimum strength) but not always one of minimum weight. As already implied, in a statically indeterminate structure the stress in a particular part is affected not only by the part itself but also by changes in all other parts of the structure; this would also make a purely intuitive re-sizing to achieve the required stress levels throughout the structure virtually impossible, or at least highly time consuming. For any other than the smallest structures, the number of finite element analyses required for any such re-sizing procedure can soon become prohibitive. Use of a formal optimization procedure can greatly reduce the number of iterations required, and generally leads to a better design.

Lack of insight into the design problem, when a finite element analysis is used, is of course inherent in the purely numerical nature of such an analysis. This can be improved by use of a so-called sensitivity analysis, in which the change in stress in all parts of the structure resulting from some change in thickness (or other dimension) in any component of the structure is calculated. Use of computer graphics becomes essential to handle the large quantity of data generated and to present this data to the designer in a convenient form to enable him to improve his design. Sensitivity data also provides a basis for "what-if" studies to predict the effect the effect of design changes. Unlike sensitivity, which is strictly the derivative of stress (or some other response of the structure) with respect to a particular design variable for the current values of the design variables, a "what-if" study allows the user to specify appropriate changes in any or all of the design variables, and to assess the effect on the structure. The same sensitivity data can also be used in an optimization procedure for a minimum weight design satisfying stress constraints. This can serve as the starting point for a more practical design, with the benefit of sensitivity data to help the designer to appreciate the consequences of such changes.

The Program CuFus

The program CuFus (design of a CUt-out in a pressurised FUSelage) has been developed to implement the automated model generation, sensitivity analysis and optimization referred to above in a user-friendly, design environment [8] [9]. Large cut-outs in a pressure cabin, like those for doors, can be very fatigue sensitive. The stress concentration caused by the presence of the cut-out for a door may be aggravated by use of the door in service, with considerably increased chance of accidental damage. When a small dent or other damage has occurred, a fatigue crack might be only a matter of time. Fatigue damage endangers safety, and can lead to expensive repairs. For these reasons stress levels must be kept below carefully defined maximum levels.

CuFus is a special-purpose program for the design problem sketched above. The program enables the user to define the shape of the cut-out and the geometry of the fuselage containing it, including the position of stringers and frames, and to define doubler-plates and edge members reinforcing the cut-out. Initial mesh generation is based on this geometry. A standardised (though highly adaptable) geometry is a necessary restriction to achieve a user-friendly geometry definition and to enable an automated mesh generation. However, most of the facilities within CuFus can be used for a much wider range of design problems than the cut-out in a fuselage, creating in fact a "toolbox" of computer routines for more general use. In summary, options offered by CuFus are as follows:

- fast, easy initial model generation
- fully interactive, user-friendly model editing
- preparation for either linear or non-linear finite element calculation
- preparation for a sensitivity analysis and graphical display of the results of such an analysis
- carrying out "what-if" studies
- preparing and performing a design optimization.

The program uses MSC/Nastran for the finite element analysis, sensitivity and optimization, together with Patran for pre- and post-processing. Maximum use is made of the graphics capability of the latter software package. For this reason CuFus is written almost entirely in the PCL-language offered by Patran. All software produced is in addition to available commercial software, i.e. no source code modifications of the commercial software are called for.

Figure 9 shows the finite element model of a fuselage with door, windows and floor structure produced by CuFus. This model can be generated very quickly from a limited amount of data. An initial mesh is generated at the same time as the geometric model definition. Built-in mesh refinement procedures enable the user to obtain more detail in critical areas such the corner of the cut-out (figure 10 shows part of the finite element model with local mesh refinement). While geometric changes in the cut-out can require significant changes in the finite element model, such changes are readily made in CuFus and in a relatively short time. Property definition and assignment also takes place interactively. Figure 11 shows one of the available windows, in this case one in which standard stiffener sections may be selected. Design elements for both

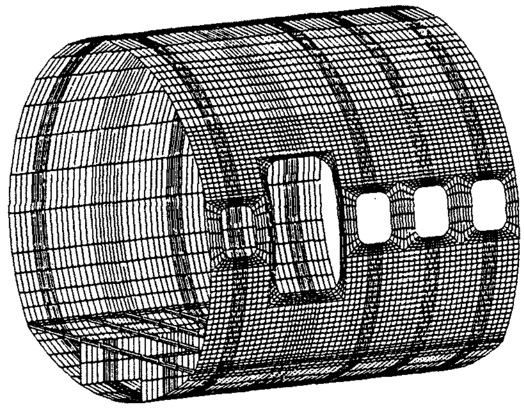


Figure 9. Finite element model of fuselage with door in CuFus.

sensitivity analysis and optimization consist of appropriately chosen groups of finite elements. These may be freely chosen by the designer to represent edge reinforcement, doubler plates and other features. In the case of doubler plates, elements are selected so as to properly represent the chosen extent of a proposed doubler. However, if a single doubler is represented by a number of design elements, an indication can be obtained of the best location of the doubler. Figure 12 shows the form used for defining design variables and constraints. Figure 13 shows the definition of design variables, and their initial values, in a particular example (bold numbers refer to a particular design element; design variables for the skin and doublers are thicknesses, for other reinforcing members cross-sectional areas).

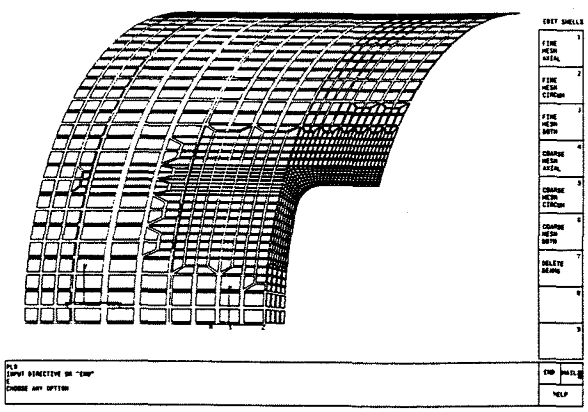


Figure 10. Corner of cut-out showing local mesh refinement.

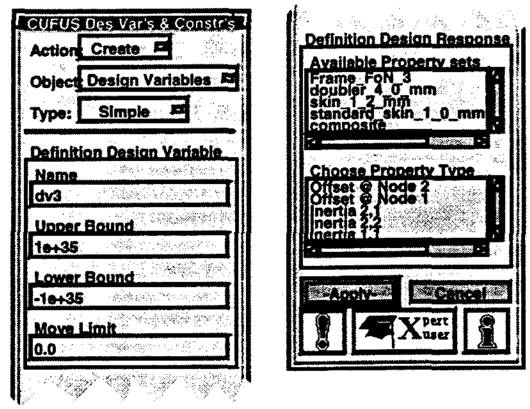


Figure 12. Form for defining design variables and constraints.

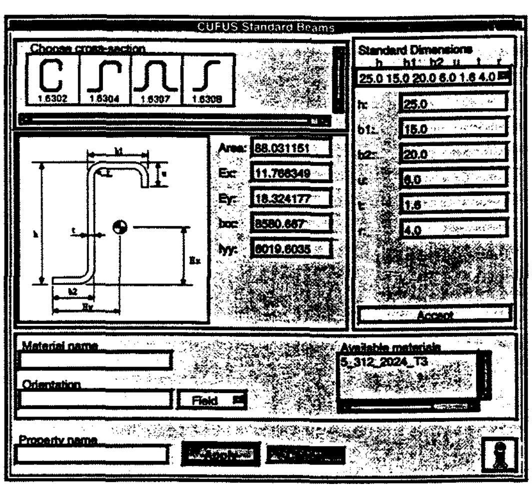


Figure 11. Window for selecting standard stiffener sections.

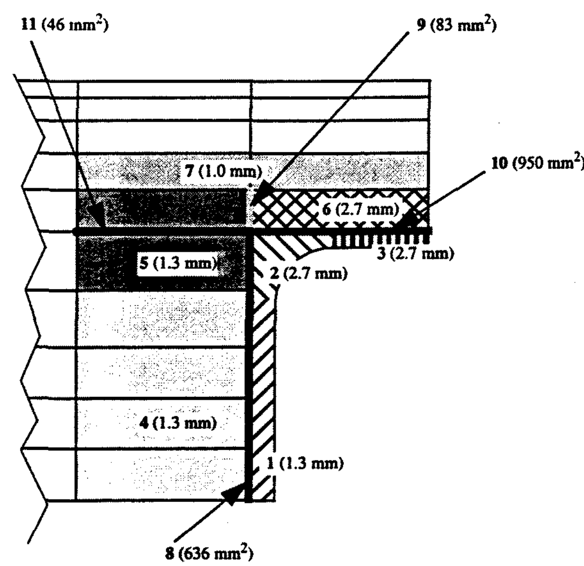


Figure 13. Definition of design variables for reinforcement.

Sensitivity Analysis and Optimization

With regard to stresses, the sensitivity data produced by CuFus is $\partial\sigma_j / \partial x_i$, evaluated at the current design point, where σ_j is the maximum stress at some point j in the structure and x_i is the design variable relating to a design element i. A typical sensitivity plot (figure 14) shows the change in stress due to doubling the thickness of a doubler-plate above the door (design variable 7, see figure 13). Only the part of the structure near

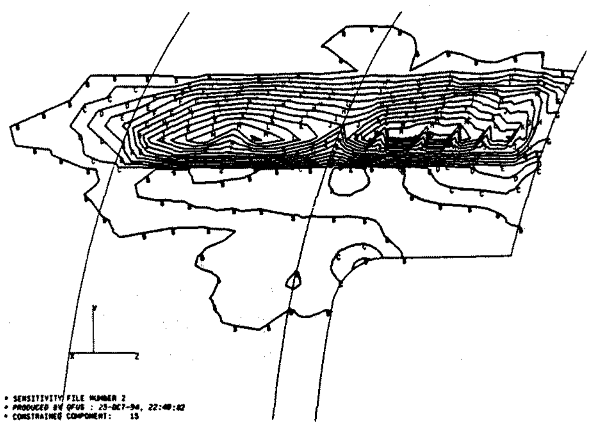


Figure 14. Typical sensitivity plot (change in stress due to doubling design variable 7).

the rounded corner of the cut-out is shown in the figure. A highly complex behaviour is observed, with reduction in stress at the doubler-plate itself but *increase* in stress (positive contours) at certain other critical points. This confirms the earlier statement that an intuitive design process would be ineffective, if done without the benefit of a sensitivity analysis.

The same sensitivity data may be used in a "what-if" analysis. This enables the designer to explore the effect of specific changes in the design. This can be a powerful means of gaining insight into the design problem. The program calculates:

$$\sigma_j' = \sigma_j + \Delta\sigma_j = \sigma_j + \sum_i \frac{\partial\sigma_j}{\partial x_i}\Delta x_i$$

Figures 15(a) and 15(b) show a typical result of such a "what-if" analysis (design variable 1, the thickness at the side of the cut-out, is increased from 1.3 to 1.4 mm and design variable 2 , the thickness at the corner of the cut-out, from 2.7 to 3.0 mm, i.e. changes of about 8% and 11% respectively). The effects of a design change using "what-if" are displayed in only a few seconds. In this case the result of a re-analysis of

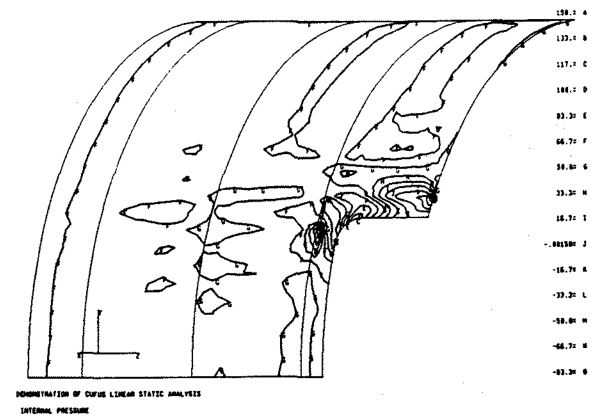


Figure 15(a). Stress contours at start of "what-if" analysis.

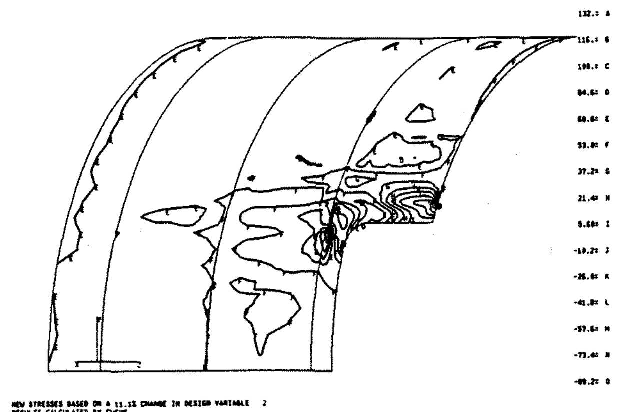


Figure 15(b). Modified stress contours after "what-if" analysis.

the modified design was indistinguishable from figure 15(b), confirming that the linearization implied in the above equation is satisfactory.

The sensitivity data generated may also be used in a formal optimization, making use of the standard Nastran optimizer. Post-processing of the results of an optimization has been extended in CuFus (figure 16). The optimization history of any design variable can be displayed, as well as maximum constraint violation and reduction in objective function - the weight of the structure. Convergence is generally adequate in only a few iterations; this can greatly reduce the cost of repeated finite element analyses in the conventional design procedure. If necessary the optimization can be repeated from a new initial design, to explore the possibility of local minima in the design problem.

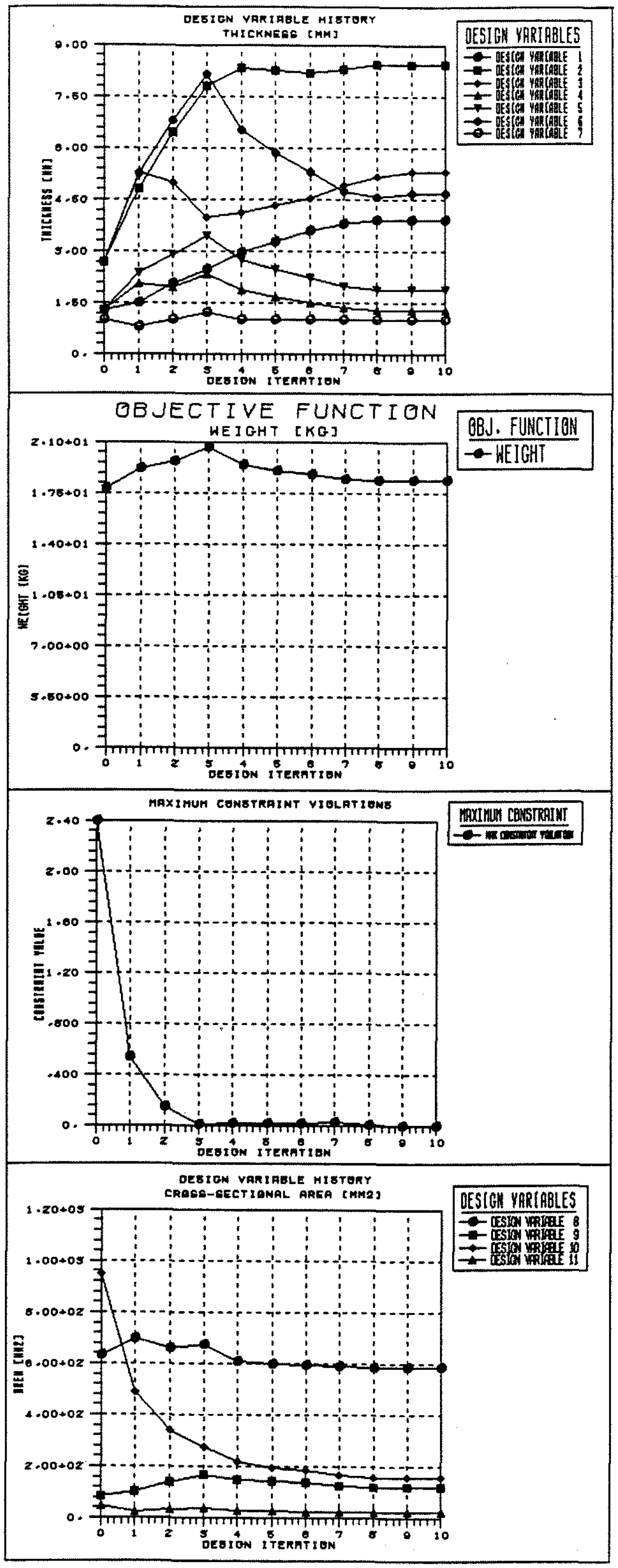


Figure 16. Optimization history (design variables, maximum constraint violation and objective function).

Conclusion

Different approaches to the development of programs to serve as a direct aid to the designer in various stages of the design process are described here. In all cases some restriction of the geometric definition of the structure has been necessary in order to provide a fast and easy to use design program. However, the methods described are readily extended to other structural design problems. Considerable emphasis is given to allowing the user maximum design freedom within the stated geometric limitations, and to providing as much information as possible to the designer about the progress of the design. With programs like WingDesign and SaPanO parametric studies are readily performed, and can provide much insight into the nature of the design problem. With programs such as CuFus, based on finite element analysis, this same insight can be provided by making full use of "what-if" studies and available sensitivity data. The run-time for WingDesign and SaPanO is very short - on a modern personal computer generally less than one minute. The total time taken to reach a design is therefore primarily dependent on the activity of the user. Also CuFus is very fast - a complete design cycle, including of course generation and up-dating of the finite element model, can usually be completed in less than one day. Development of the programs is continuing, in particular with the further development of the integrated package AeSOpS, and the creation of a more general "toolbox" of computer routines from those developed for CuFus.

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