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Engineering Notes

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Development of a Wing Preliminary Structural Analysis Code

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Nomenclature

A = cross-sectional area, mm^2
E = Young's modulus of elasticity, MPa
F_C = column critical stress, MPa
F_{cs} = crippling stress, MPa
F_{cy} = compressive yield stress, MPa
L = equivalent column length, mm
t = thickness, mm
w = effective sheet width, mm
ρ = radius of gyration, mm

Introduction

THE typical aircraft structural design process contains numerous iterations from the conceptual design phase to the determination of final configuration. In the conceptual design phase and in the early stages of the preliminary design, careful sizing of the structural elements has vital importance. Accurate sizing of these elements ensures accurate preliminary strength and weight estimates, changes to which can be extremely costly in the ensuing design stages. To reduce the costs, man-hours, and delays in schedule, the aircraft industry developed analysis tools at different levels of sophistication for nearly three decades. Equivalent Laminated Plate Solutions (ELAPS),[1,2] Generic Transport Aircraft Knowledge-Based Design Tool (GTA-KBDT),[3] and ALACA[4] are some of those.

Wing Preliminary Structural Analysis Code (WPSAC) is similar to those computer codes in some aspects. It is being developed in the TAI, Structural Design Department, Structural Analysis Group with the intention of utilization between the conceptual and preliminary design phases. The main purpose of WPSAC is the accurate sizing of structural elements. It also conveniently enables one to easily and rapidly investigate different possible geometries. Presently the package is not capable of automatic sizing; however, developments are in progress. By examining the resulting margins of safety, the required improvements on the dimensions are done manually.

This study presents the developed program and gives the theory for spar caps and stringers stress analyses. As failure mode criteria, crippling is chosen for spar caps, and the column buckling is analyzed for stringers. A conceptual aircraft wing is studied, and the relevant stress results are also shown.

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Description of the Developed Code

The program package WPSAC consists of two parts. The first part is entitled Wing Preliminary Finite Element Modeling Code (WPFEMC), and its task is to create the wing finite element model based on the given inputs. Finite element models of various wing configurations (any forward and backward swept, any dihedral and incidence, any airfoil shape for each wing box, flap and aileron, etc.) can be created. The second part is entitled Wing Preliminary Stress Analysis Code (WPSTAC). This portion is responsible for all stress analysis calculations. The structure of the package is shown in Fig. 1, as are detailed individual tasks of the each code.

However, the program has some limitations mostly in the modeling. For example, no leading-edge high-lift device or control surface can yet be located. Furthermore composites cannot be modeled yet. In addition, stringers have to be continuous through the span, and the skin thicknesses must be constant between two ribs.

Modeling of Wing Structural Elements

Because spar caps are assumed to have bending capability, in the modeling of the spar caps the bar elements are utilized. Spar web elements and ribs primarily carry shear and some normal stresses,

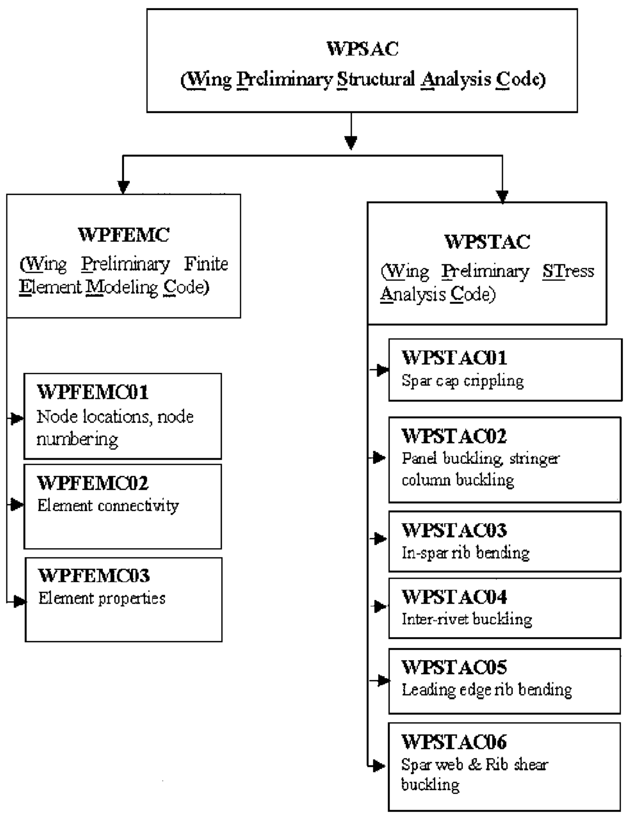

Fig. 1 General layout of the WPSAC code.

but their deformations are mainly caused by shear. Therefore, like most aircraft companies, shear panel elements are used in the modeling of spar webs and ribs. In modeling of the skin, shear panel elements are selected. But because the shear panel had no capability of carrying in-plane normal stress, the rod elements were located to all of the four edges of a shear panel. Where the effect of local bending moment is not significant and in primarily axial load-carrying structures, rod elements are used. Stringers, rib flanges, and stiffeners fall into this category.

WPSAC Stress Analysis

After the finite element model is run, the internal forces are taken from the MSC\NASTRAN® output file by WPSTAC, and stresses on each element are computed with the methods described in Refs. 5 and 6. WPSTAC also calculates the allowable stresses and finds margins of safety for all elements. The following section gives the brief theoretical background for spar-cap crippling and stringer column buckling analyses.

Applied Stresses

Spar Caps

Spar-cap stresses are calculated from grid point force balance data. At a specified grid, elements at the left- and right-hand side of that specific wing station are determined, and the forces acting on that grid are then found.

Stringers

For stringer column buckling stress analysis, the resultant internal axial forces and stringer cross-section geometric properties are used to calculate the applied stresses.

Critical Stresses

Spar-Cap Crippling Stresses

For the determination of the crippling stresses the Gerard Method is used.[5]

For sections with distorted unloaded edges such as angles, tubes, multicorner sections, and stiffened panels, the following crippling stress equation applies within ±10% limits:

$$F_{cs}/F_{cy} = 0.56\left[(gt^2/A)(E/F_{cy})^{\frac{1}{2}}\right]^{0.85} \tag{1}$$

where g denotes the number of flanges that compose the composite section, plus the number of cuts necessary to divide the section into series of flanges.

For sections with straight unloaded edges such as plates, tee, cruciform, and H sections, the following equation for crippling stress applies within ±5% limits:

$$F_{cs}/F_{cy} = 0.67\left[(gt^2/A)(E/F_{cy})^{\frac{1}{2}}\right]^{0.40} \tag{2}$$

For two corner sections Z, J, and channel sections, the following equation applies within ±10% limits:

$$F_{cs}/F_{cy} = 3.2\left[(t^2/A)(E/F_{cy})^{\frac{1}{3}}\right]^{0.75} \tag{3}$$

Column Buckling Stresses

Column buckling calculation is performed for skin-stringer analysis, and it is an iterative process. The iteration starts with the assumption that the column buckling critical stress equals the crippling stress. Then the effective sheet width w is calculated from Eq. (4). Afterwards the area and the moment of inertia of the stringer cross section are computed about neutral axis together with the effective skin. Later by using the Euler–Johnson equation given in Eq. (5) (Ref. 5), F_C is found, and this value is inserted into the effective sheet equation. The new effective skin width is calculated according to the new F_C, and the steps are repeated until F_C is converged to a prescribed value.

$$w = 1.7t\sqrt{E/F_{cs}} \tag{4}$$

$$F_C = F_{cs} - \left(F_{cs}^2/4\pi^2 E\right)(L/\rho)^2 \tag{5}$$

Analysis of a Conceptual Wing

This section presents a study performed for a conceptual wing. The general configuration of the wing box is presented in Table 1.

Whereas the front spar is composed of back-to-back angles at the top and bottom and the web, the rear spar is built with angles at the top and bottom and web. The stringers are Z shaped and have constant cross sections along the span. The skin, web, and rib thicknesses are constant along the spanwise direction.

It is known that the wing structural elements are more susceptible to failure under compression than tension in the static stress analysis. Therefore this study, for brevity, only presents the stress analysis results of compression side members.

In Fig. 2 the ultimate and allowable stresses of the front and rear spar upper caps are plotted as computed by WPSTAC. The allowable stresses for upper caps are the crippling stresses.

The ultimate and allowable stresses of the top stringers, as determined by WPSTAC, are shown in Fig. 3. The allowable stresses for top stringers are column buckling stresses.

Table 1 Wing box configuration

Characteristics	Value
Airfoil type	NACA23012
Leading-edge sweep angle	5.71 deg
Root cord	1500 mm
Dihedral angle	5 deg
Incidence angle	2 deg
Taper ratio	0.667
Structural semispan	5000 mm
No. of spars	2
No. of ribs	15
No. of top stringers	3
No. of bottom stringers	3

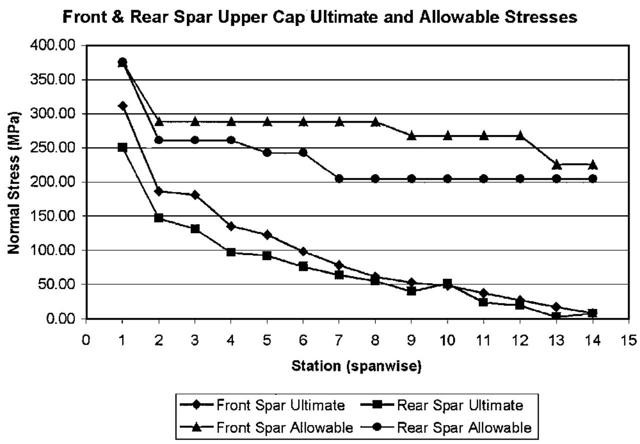

Fig. 2 Front spar and rear spar upper cap stresses.

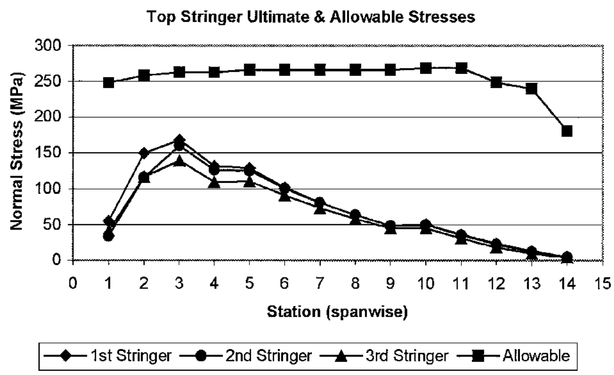

Fig. 3 Top stringer stresses.

Conclusions

The main objective of the WPSAC package is to provide accurate first sizing of wing structural elements at very early stages of the design process. The requirement for such a program like WPSAC becomes apparent considering the possible redesign problems as a result of the improperly conducted trade and initial sizing studies. WPSAC has been developed according to the modeling and stress analysis techniques employed at TAI.

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Analytical Solution for Wing Dihedral Effect

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Nomenclature

a_n	=	coefficients in the classical infinite series solution to Prandtl's lifting line equation
b	=	wingspan
$C_{L,\alpha}$	=	lift slope for the complete finite wing
$\tilde{C}_{L,\alpha}$	=	local in situ section lift slope, including the effects of local wing downwash
$C_{\ell,\beta}$	=	roll stability derivative, that is, change in rolling moment coefficient with respect to sideslip angle
c	=	local wing section chord length
R_A	=	aspect ratio, b^2/S
S	=	wing planform area
V	=	airspeed
v	=	sideslip component of relative wind
y	=	spanwise coordinate
β	=	sideslip angle
Γ	=	wing dihedral angle
$(\Delta C_\ell)_\Gamma$	=	contribution to the rolling moment coefficient that results from sideslip combined with wing dihedral
$(\Delta C_{\ell,\beta})_\Gamma$	=	contribution of wing dihedral to the roll stability derivative
θ	=	change of variables defined by Eq. (5)

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Introduction

FOR a conventional airplane, the change in rolling moment due to sideslip is heavily influenced by the dihedral angle of the wing. Wing dihedral affects the roll stability derivative of an airplane because it causes the lift on the right and left semispans to respond differently to sideslip. As shown in Fig. 1 for a wing with positive dihedral, sideslip produces an increase in angle of attack on the windward semispan and a decrease in angle of attack on the leaside semispan. When the sideslip component of relative wind is resolved into components parallel with and normal to each semispan, as shown in Fig. 1, the upward normal component is $v \sin\Gamma$ on the right semispan and $-v \sin\Gamma$ on the left semispan. For small aerodynamic angles, the sideslip velocity can be closely approximated as the product of the airspeed and sideslip angle. Likewise, the angle of attack is closely approximated as the upward normal component of relative wind divided by the airspeed. Thus, sideslip produces a change in angle of attack that can be closely approximated for the right and left semispans as $\beta \sin\Gamma$ and $-\beta \sin\Gamma$, respectively.

The differential in angle of attack between the right and left semispans creates a differential in lift, which in turn produces a rolling moment. With the standard sign convention, lift generated on the left semispan ($y < 0$) produces a positive rolling moment, whereas lift generated on the right semispan ($y > 0$) produces a negative rolling moment. Thus, the rolling moment arm for the lift on any wing section is $-y$. When the small angle approximations discussed earlier are used, the net contribution to the rolling moment coefficient that results from sideslip combined with wing dihedral can be written

$$(\Delta C_\ell)_\Gamma = -\frac{\beta \sin\Gamma}{Sb}\int_{y=-b/2}^{b/2} \tilde{C}_{L,\alpha}|y|c\,\mathrm{d}y \tag{1}$$

where $\tilde{C}_{L,\alpha}$ includes the effects of local induced downwash. In general, the local induced downwash varies with spanwise position. Thus, $\tilde{C}_{L,\alpha}$ depends not only on the airfoil section geometry but also on the position that the section occupies along the span of the finite wing. Even if the section geometry and airfoil section lift slope are constant over the span of the wing, the in situ section lift slope can vary with spanwise position. Typically, the in situ section lift slope will vary from a maximum at the midspan to zero at the wingtips.

The local induced downwash and in situ section lift slope will be affected by the sideslip. Thus, the derivative of Eq. (1) with respect to β is

$$\frac{\partial}{\partial\beta}(\Delta C_\ell)_\Gamma = -\frac{\sin\Gamma}{Sb}\int_{y=-b/2}^{b/2} \tilde{C}_{L,\alpha}|y|c\,\mathrm{d}y - \frac{\beta\sin\Gamma}{Sb}\int_{y=-b/2}^{b/2}\frac{\partial\tilde{C}_{L,\alpha}}{\partial\beta}|y|c\,\mathrm{d}y$$

However, the roll stability derivative $C_{\ell,\beta}$ is evaluated at $\beta = 0$ and the contribution of wing dihedral to this aerodynamic derivative can be written

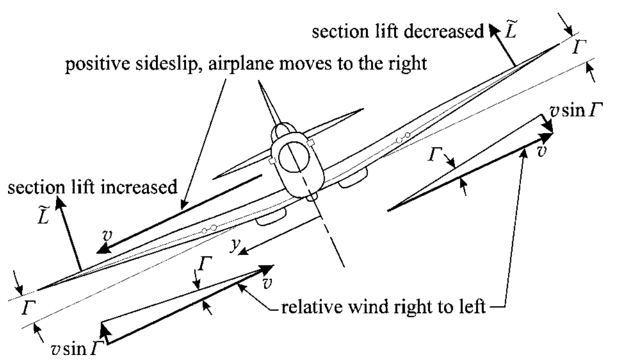

Fig. 1 Effect of sideslip and wing dihedral on local section lift.