NASA-CR-207164

Final Report for NASA NCA2-5025

Simplified Aerodynamic and Structural Modeling for Oblique All-Wing Aircraft —Phase II: Structures

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September 1994

Introduction

The following pages describe the results of work performed under NASA Consortium NCC2-5025, including the development of a program for structural analysis and weight estimation for an oblique all-wing aircraft.

Any aircraft preliminary design study requires a structural model of the proposed configuration. The model must be capable of estimating the structural weight of a given configuration, and of predicting the deflections which will result from foreseen flight and ground loads. The present work develops such a model for the proposed Oblique All Wing airplane. The model is based on preliminary structural work done by Jack Williams and Peter Rudolph at Mdng, and is encoded in a FORTRAN program. As a stand-alone application, the program can calculate the weight CG location, and several types of structural deflections; used in conjuncbon with an aerodynamics model, the program can be used for mission analysis or sizing studies.

Program Structure

The program consists of a group of analysis and drawing subroutines which communicate with each other and with a database through the interface package, GENIE[1]. The database contains all physical parameters necessary to describe the airplane: element dimensions, material parameters, component locations, weights of fixed equipment, etc. Figure 1 shows the structure of the interaction between the program's subroutines and the database.

Analysis routines

- ***PlateBeamProp***[2] calculates structural properties of plate-like and beam-like elements used to build up the wing section structure.
- ***CompSec*** computes, for a given wing section, such properties as structural weight per unit span, section CG location (fore and aft), and wing stiffness (EI).
- ***Buildwing*** assembles section properties from *CompSec* into a single beam model for the whole airplane, adds in the user-defined fixed equipment weight distribution, and computes the total airplane weight, weight distribution, CG location, and bending stiffness.
- ***WingSupport*** finds the forces to which the wing will be subjected, both in flight and when resting on its landing gear.
- ***InternPress*** describes the cabin pressure, for use in calculation of the skin pressurization pillowing.
- ***Deflection*** takes the results of all the above routines, and calculates the wing bending moments and deflections across the span.

Drawing Routines

- ***Planform*** draws the planform of the wing described in the database, including engine and fin locations; lines on the drawing mark locations where the wing section is explicitly defined in the database.

[1] Available from Desktop Aeronautics, PO Box 9937, Stanford, CA 94305.
[2] Note that throughout the rest of this text, words in *italic type face* denote program subroutines or names in the database.

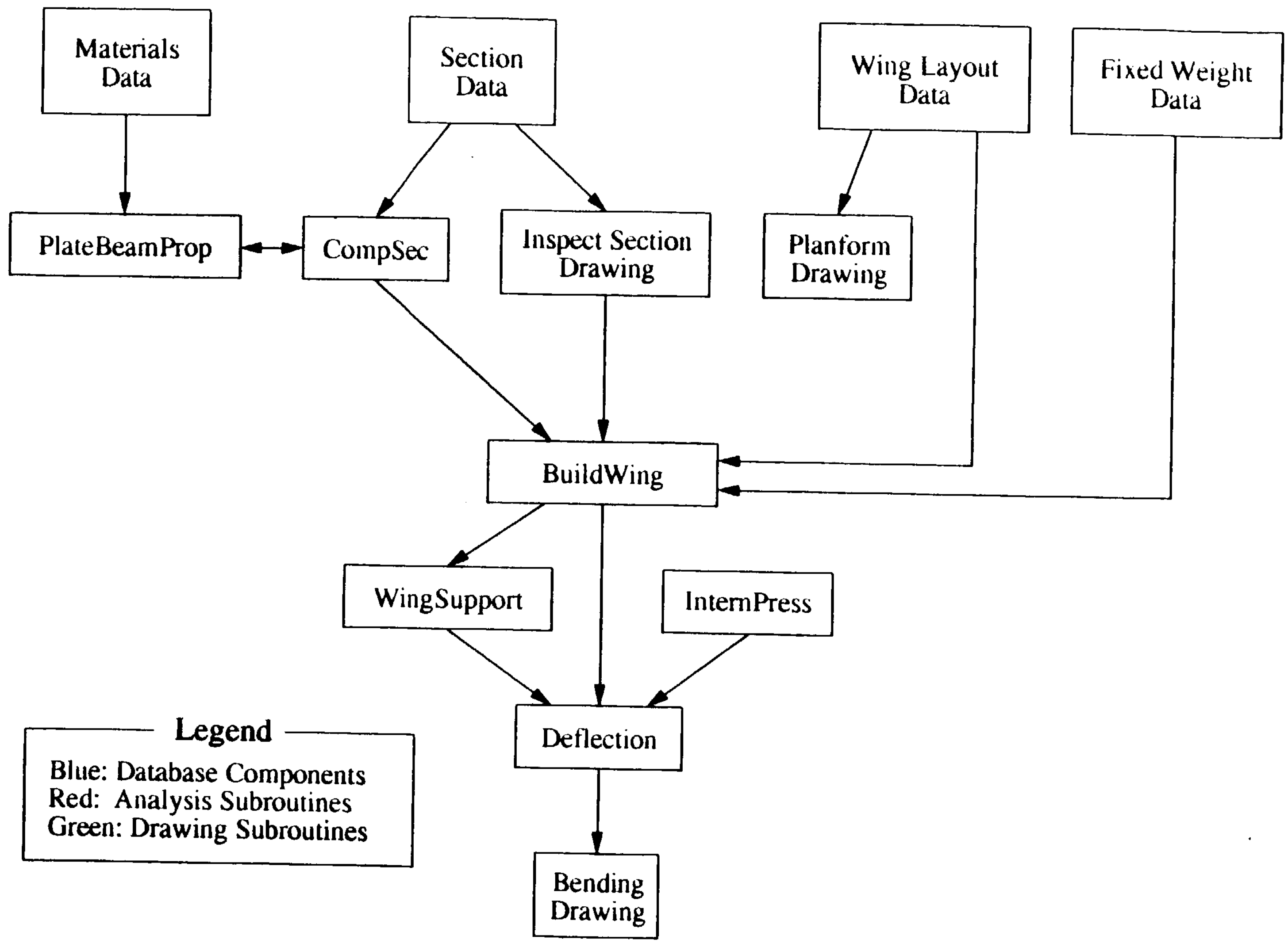


Figure 1 A flow chart of the program, describing the interactions between the analysis subroutines, drawing subrtouines, and database components.

- ***InspectSection*** is an interactive routine which allows the user to graphically examine the parameters of the wing section he has defined in the database.
- ***Bending*** produces a front view of the airplane, including the bending deflections calculated by the analysis routines.

Wing Description

The wing is modeled as a slender beam of slowly varying cross section. The database defines *NStations* spanwise stations (*StaStation()*, indexed from 1 to *NStations* from the left to right across the span), where the moments and deflection are to be calculated. Structural properties are calculated at several (fewer than *NStations*) locations where the wing section is explicitly defined (see Section Description below), and linearly interpolated to the *NStations* stations. All wing properties are assumed to vary linearly between these stations, but may jump discontinuously across each station, requiring that two values be defined for each property at each station, a "l" and a "r" value (see figure 2). The following properties are calculated or interpolated at each station:

StalEInertia(), StarEInteria()	Wing stiffness distribution
StalLinDens(), StarLinDens()	Weight distribution
StalCGx(), StarCGx()	Chordwise local CG location
StalCentroidx(), StarCentroidx()	Chordwise section centroid location
StalChord(), StarChord()	Local wing chord
Stallex(), Starlex()	Local leading edge position
Staltoverc(), Startoverc()	Local thickness to chord ratio
Stalflapc(), Starflapc()	Local flap chord
StalmcPillCoeff(), StarmcPillCoeff()	Pillowing coefficient
StalmcBuckCoeff(), StarmcBuckCoeff()	Buckling coefficient

Section Description

Each section is defined by specifying 48 parameters: 14 geometric parameters which describe the airfoil, and 34 material parameters for the major section components. The 14 geometric parameters define a rough outline of the airfoil by designating the chordwise location, thickness, and chamber (in units of local chord, *SecChord*) at four stations (see Figure 3):

Secfsxoverc(), Secfstoverc(), SecfsCamber()	Forward spar
SecCrestxoverc(), SecCresttoverc(), SecCrestCamber()	Crest
Secrsxoverc(), Secrstoverc(), SecrsCamber()	Rear spar
Secchxoverc(), Secchtoverc(), SecchCamber()	Control hinge

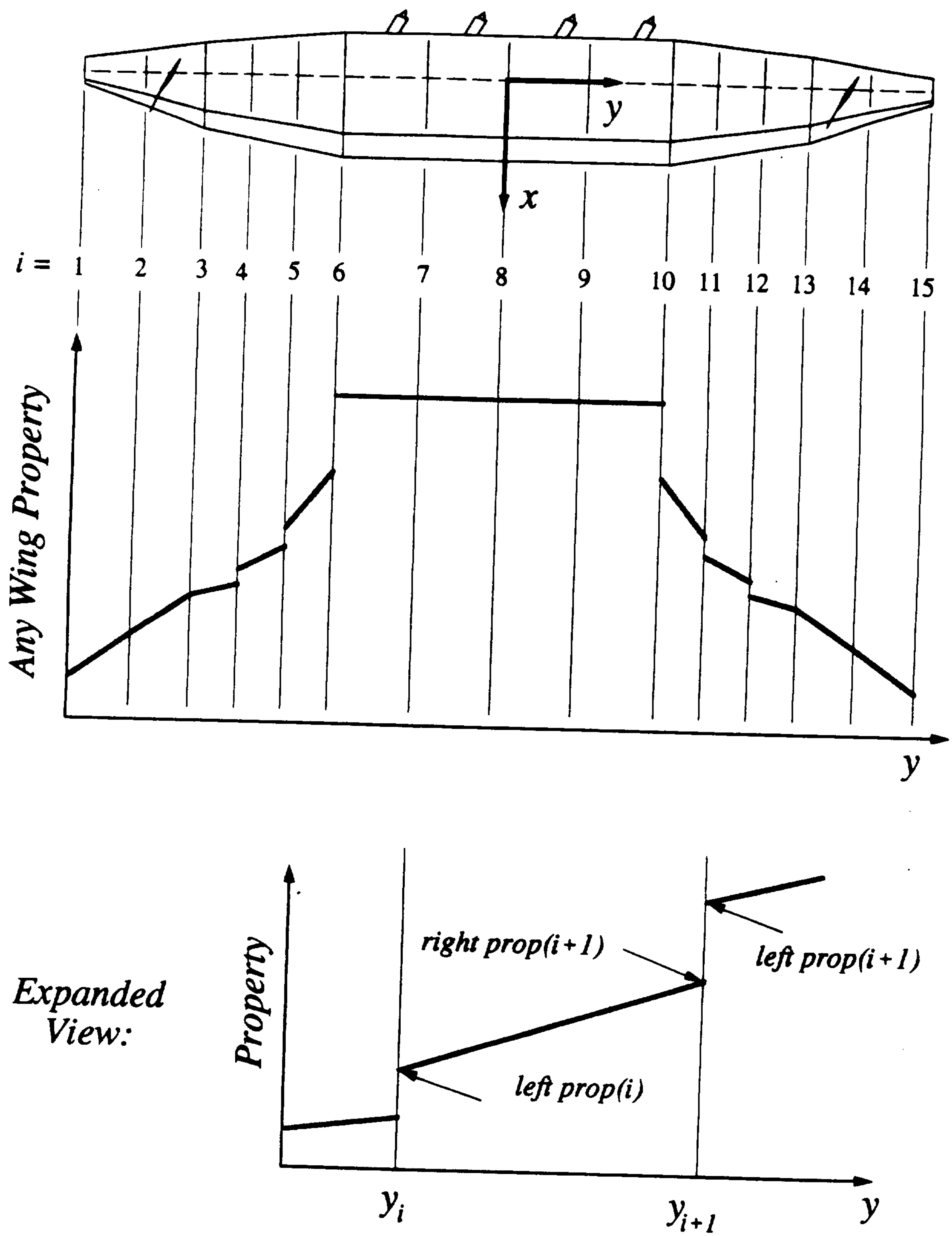


Figure 2 All the wing properties are explicitly defined or calculated at a number of stations, and assumed to vary linearly elsewhere. Discontinuous changes in properties require that a left and a right value be recorded for each property at each station.

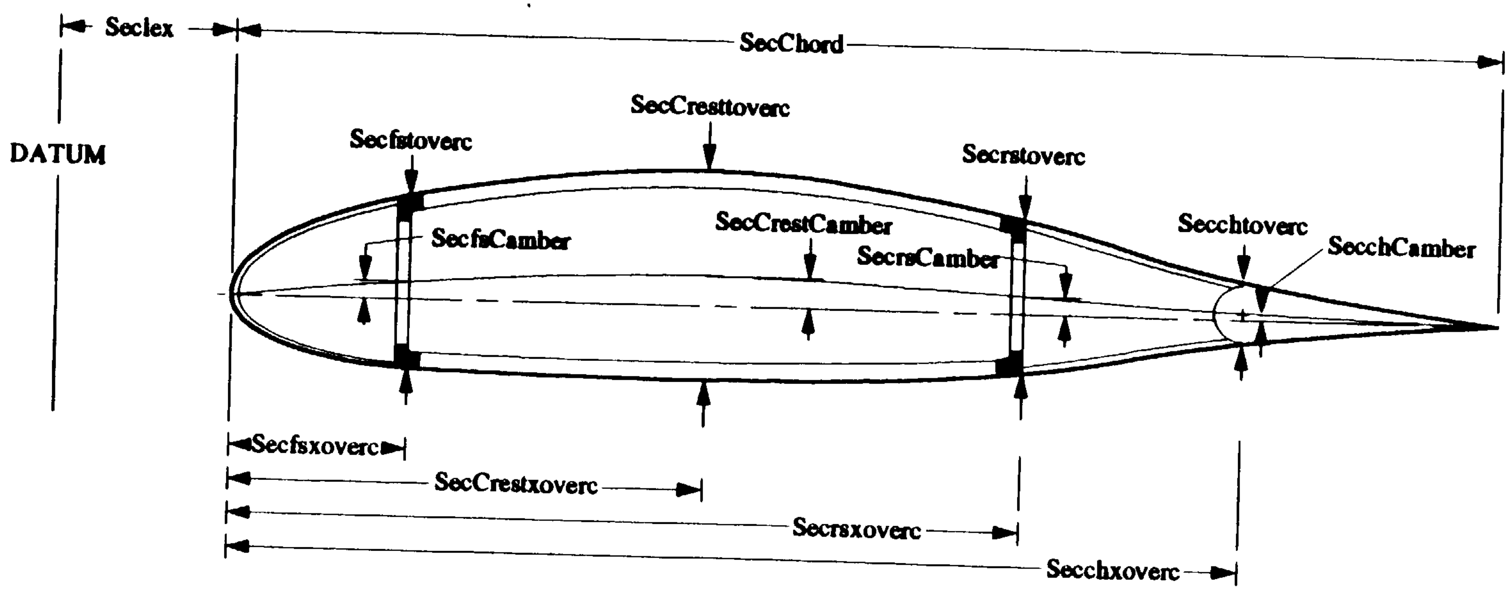


Figure 3 Fourteen parameters define the wing section geometry.

The section's location fore-and-aft is defined by its leading edge position in inches (*lex*) relative to the aircraft datum.

The 34 material parameters describe two types of section elements (see Figure 4): plate-like members (e.g. skins, spars, ribs), and beam-like members (e.g. spar-skin splices, rib-chords). Each plate-like element is defined by its outer thickness, skin thickness, and core type:

SecleSkinOT(), SecleSkinST(), SecleSkinCT()	Leading edge skins
SecmcSkinOT(), SecmcSkinST(), SecmcSkinCT()	Midchord skins
SecteSkinOT(), SecteSkinST(), SecteSkinCT()	Trailing edge skins
SecfsOT(), SecfsST(), SecfsCT()	Forward spar material
SecfsOT(), SecfsST(), SecfsCT()	Rear spar material
SecmcRibOT(), SecmcRibST(), SecmcRibCT()	Midchord ribs
SecteRibOT(), SecteRibST(), SecteRibCT()	Trailing edge ribs

The outer thickness is defined as the total plate thickness, including all core material and facing sheets. The skin thickness is taken to mean the thickness of the high density facing sheet material attached to the outside of the core material. The plate core is either of macro-core or a titanium core material.

Each beam-like element is described by a beam depth and an area fraction:

SecfsCapD(), SecfsCapAF()	forward spar-skin splices
SecrsCapD(), SecrsCapAF()	rear spar-skin splices
SecleRibTubeD(), SecleRibTubeAF()	leading edge rib tubes
SecleRibChordD(), SecleRibChordAF()	lead edge rib chords
SecmcRibChordAF()	midchord rib-skin splices
SecteRibChordAF()	trailing edge rib chord

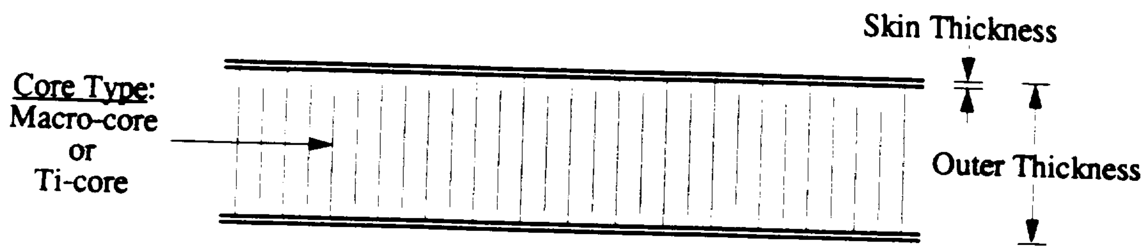
All beam elements are assumed to be made of resin transfer molding (RTM). The bending inertia of the wing section depends strongly on the amount of material in these beam-like elements, but only weakly on the beam's own bending inertia. The beam's exact geometry is therefore unimportant for the present analysis, and the beam cross section can simply be characterized by the beam size and material fraction.

Three parameters describe the rib spacing in inches:

SecleRibSpc()	leading edge ribs
SecmcRibSpc()	midchord ribs
SecteRibSpc()	trailing edge ribs

The ribs do not contribute to the wing's bending inertia, but are important for the calculation of structural weight.

Plate-like Elements



Beam-like Elements

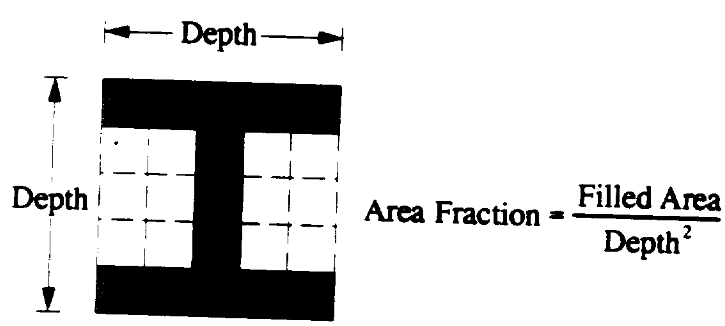


Figure 4 Plate-like section elements are described by three parameters: skin thickness, outer thickness, and core type; beam-like section elements are described by two parameters: characteristic depth, and an area fraction.

Bending Inertia

The subroutine *CompSec* computes the structural moments of inertia and desired mass properties of each user-defined section. The routine moves sequentially through each section element, adding the contributions of each element to a set of running totals. Letting i represent the section elements (e.g. leading edge skins, forward spar, etc.), and S_i be the area of the i^{th} element, the routine keeps the following sums:

$$(ES) = \sum_i \int_{S_i} E\,dS$$

$$(ES)_x = \sum_i \int_{S_i} E\,x\,dS$$

$$(ES)_z = \sum_i \int_{S_i} E\,z\,dS$$

$$(ES)_{xx} = \sum_i \int_{S_i} E\,x^2\,dS$$

$$(ES)_{zz} = \sum_i \int_{S_i} E\,z^2\,dS$$

$$(ES)_{xx} = \sum_i \int_{S_i} E\,x^2\,dS$$

$$(ES)_{xz} = \sum_i \int_{S_i} E\,xz\,dS$$

where E is the Young's modulus of each area element, dS. From these totals, the program can extract the section's neutral axis location,

$$\begin{aligned} SecCentroidx &= x_{centroid} = \frac{(ES)_x}{(ES)} \\ SecCentroidz &= z_{centroid} = \frac{(ES)_z}{(ES)}, \end{aligned}$$

and thus obtain the moments and products of inertia,

$$\begin{aligned} (EI)_{xx} &= (ES)_{zz} - z_{centroid}(ES)_z \\ (EI)_{zz} &= (ES)_{xx} - x_{centroid}(ES)_x \\ (EI)_{xz} &= (ES)_{xz} - z_{centroid}(ES)_x - x_{centroid}(ES)_z + x_{centroid} z_{centroid}(ES) \end{aligned}$$

Because $(EI)_{xz}$ will generally be non-zero, the program must account for the inertia mixing between axes. We are interested in bending deflections about the x-axis, so we form the combination,

$$SecEInertia = (EI) = \frac{(EI)_{xx}(EI)_{zz} - (EI)_{xz}^2}{(EI)_{zz}}.$$

The desired mass properties are calculated in a similar manner:

$$SecLineDensity = \lambda_m = \sum_i \int_{S_i} \rho \, dS$$

$$(\lambda_m)_x = \sum_i \int_{S_i} \rho \, x dS$$

$$(\lambda_m)_z = \sum_i \int_{S_i} \rho \, z dS$$

$$SecCGx = x_{CG} = \frac{(\lambda_m)_x}{\lambda_m}$$

$$SecCGz = z_{CG} = \frac{(\lambda_m)_z}{\lambda_m}$$

where *SecLineDensity* is the mass of the structure per unit length of span and *SecCGx* and *SecCGz* represent the center of mass location.

Bending Deflection

Calculation of the wing bending moment and deflection is accomplished by analytical integration of the applied loads and wing properties. We start be defining the total load applied to the wing at any spanwise location as the wing weight per unit span minus the supporting force per unit span:

$$P(y) = Weight(y) - Support(y)$$

We assume that this load varies linearly between defined stations, so that the load may be written as

$$P(y) = P_i^{left} + (y - y_i)\frac{P_{i+1}^{right} - P_i^{left}}{\Delta y_i}, \quad \text{for } y_i < y < y_{i+1},$$

with the index i running from 1 to *NStations*. We have assumed the following definitions:

$$\begin{aligned} P_i^{left} &= Weight^{left}(y_i) - Support^{left}(y_i) \\ P_i^{right} &= Weight^{right}(y_i) - Support^{right}(y_i) \\ \Delta y_i &= y_{i+1} - y_i \end{aligned}$$

Now we can calculate the shear loading and bending moment applied to the wing by integrating the linearly interpolated P(y):

$$\begin{aligned} Shear(y) &= \int_{y_1}^{y} P(y')dy' \\ Shear_1 &= 0 \\ Shear_{i+1} &= Shear_i + \frac{P_i^{left} + P_{i+1}^{right}}{2}\Delta y_i \\ Moment(y) &= \int_{y_1}^{y} P(y')y'dy' \\ Moment_1 &= 0 \\ Moment_{i+1} &= Moment_i + Shear_i\Delta y_i + \left(\frac{P_i^{left}}{2} + \frac{P_{i+1}^{right} - P_i^{left}}{6}\right)\Delta y_i^2 \end{aligned}$$

It is physically reasonable to assume that the inverse of the wing bending inertia varies linearly between the stations where the wing section has explicitly been defined:

$$(EI)(y) = \left[\left((EI)_i^{left}\right)^{-1} + (y - y_i)\frac{\left((EI)_{i+1}^{right}\right)^{-1} - \left((EI)_i^{left}\right)^{-1}}{\Delta y_i}\right]^{-1}, \quad \text{for } y_i < y < y_{i+1}.$$

The second derivative of the wing deflection is just the ratio of the bending moment to the bending stiffness, or

$$\frac{\partial^2 Defl}{\partial y^2}(y) = \frac{Moment(y)}{EI(y)}.$$

Combining the linearly interpolated formula for the stiffness with the above moment definition, we obtain the following polynomial solution for the second derivative of the deflection:

$$\left(\frac{\partial^2 Defl}{\partial y^2}\right)_1 = 0$$

$$\left(\frac{\partial^2 Defl}{\partial y^2}\right)_{i+1} = K_{0i} + K_{1i}(\Delta y_i) + K_{2i}(\Delta y_i)^2 + K_{3i}(\Delta y_i)^3 + K_{4i}(\Delta y_i)^4,$$

where the polynomial coefficients are given by

$$K_{0i} = Moment_i\left((EI)_i^{left}\right)^{-1}$$

$$K_{1i} = Moment_i\left[\frac{\left((EI)_{i+1}^{right}\right)^{-1} - \left((EI)_i^{left}\right)^{-1}}{\Delta y_i}\right] + Shear_i\left((EI)_i^{left}\right)^{-1}$$

$$K_{2i} = Shear_i\left[\frac{\left((EI)_{i+1}^{right}\right)^{-1} - \left((EI)_i^{left}\right)^{-1}}{\Delta y_i}\right] + \frac{P_i^{left}}{2}\left((EI)_i^{left}\right)^{-1}$$

$$K_{3i} = \frac{P_i^{left}}{2}\left[\frac{\left((EI)_{i+1}^{right}\right)^{-1} - \left((EI)_i^{left}\right)^{-1}}{\Delta y_i}\right] + \frac{P_{i+1}^{right} - P_i^{left}}{6\Delta y_i}\left((EI)_i^{left}\right)^{-1}$$

$$K_{4i} = \frac{P_{i+1}^{right} - P_i^{left}}{6\Delta y_i}\left[\frac{\left((EI)_{i+1}^{right}\right)^{-1} - \left((EI)_i^{left}\right)^{-1}}{\Delta y_i}\right]$$

Now the first derivative and deflection itself can be found by analytic integration:

$$\left(\frac{\partial Defl}{\partial y}\right)_{i+1} = \left(\frac{\partial Defl}{\partial y}\right)_i + K_{0i}(\Delta y_i) + K_{1i}\frac{(\Delta y_i)^2}{2} + K_{2i}\frac{(\Delta y_i)^3}{3} + K_{3i}\frac{(\Delta y_i)^4}{4} + K_{4i}\frac{(\Delta y_i)^5}{5}$$

$$Defl_{i+1} = Defl_i + \left(\frac{\partial Defl}{\partial y}\right)_i(\Delta y_i) + K_{0i}\frac{(\Delta y_i)^2}{2} + K_{1i}\frac{(\Delta y_i)^3}{6} + K_{2i}\frac{(\Delta y_i)^4}{12} + K_{3i}\frac{(\Delta y_i)^5}{20} + K_{4i}\frac{(\Delta y_i)^6}{30}$$

The constants of integration (which determine values for the deflection and its first derivative at $i=1$) are chosen such that both wing tips are at $z = 0$.

Results

Numerical results for the baseline airplane are shown in figures 5 through 8. Figure 5 shows the weight distribution and wing stiffness as a function of span. Note that the wing is heaviest in the region of the fuel tanks, outboard of the pressurized passenger cabin. Note, also that the weight distribution is slightly asymmetric. The only asymmetry in the baseline configuration (as it is described in the database) is location of the APU.

Figure 6 shows the wing bending moment and deflection due to an elliptical lift distribution. Note in particular that the bending moment is negative at the wing root, due to the fact that the majority of the weight is carried outboard.

Figure 7 shows the wing bending moment and deflection due to 1-g static loads applied at the landing gear. Because the airplane is nearly span-loaded during flight, the peak bending moment due to ground loads is a factor of 10 higher than the peak moment due to flight loads. Ground loads, however, apply their peak moment to the stiffest part of the wing--inboard in the pressurized passenger cabin, whereas flight loads apply their peak bending moments outboard where the wing is less stiff.

Figure 8 illustrates the magnitude of these bending deflections, compared to the scale of the airplane. In each case the total wing-tip deflection is about equal to the thickness of the wing at the root.

Table 1 is a complete airplane weight breakdown. The structural weight is computed by the program; the weights and CG locations of all fixed equipment are fixed entries in the database. The program's estimate for the structural weight of the baseline airplane is 112,345 lbs.

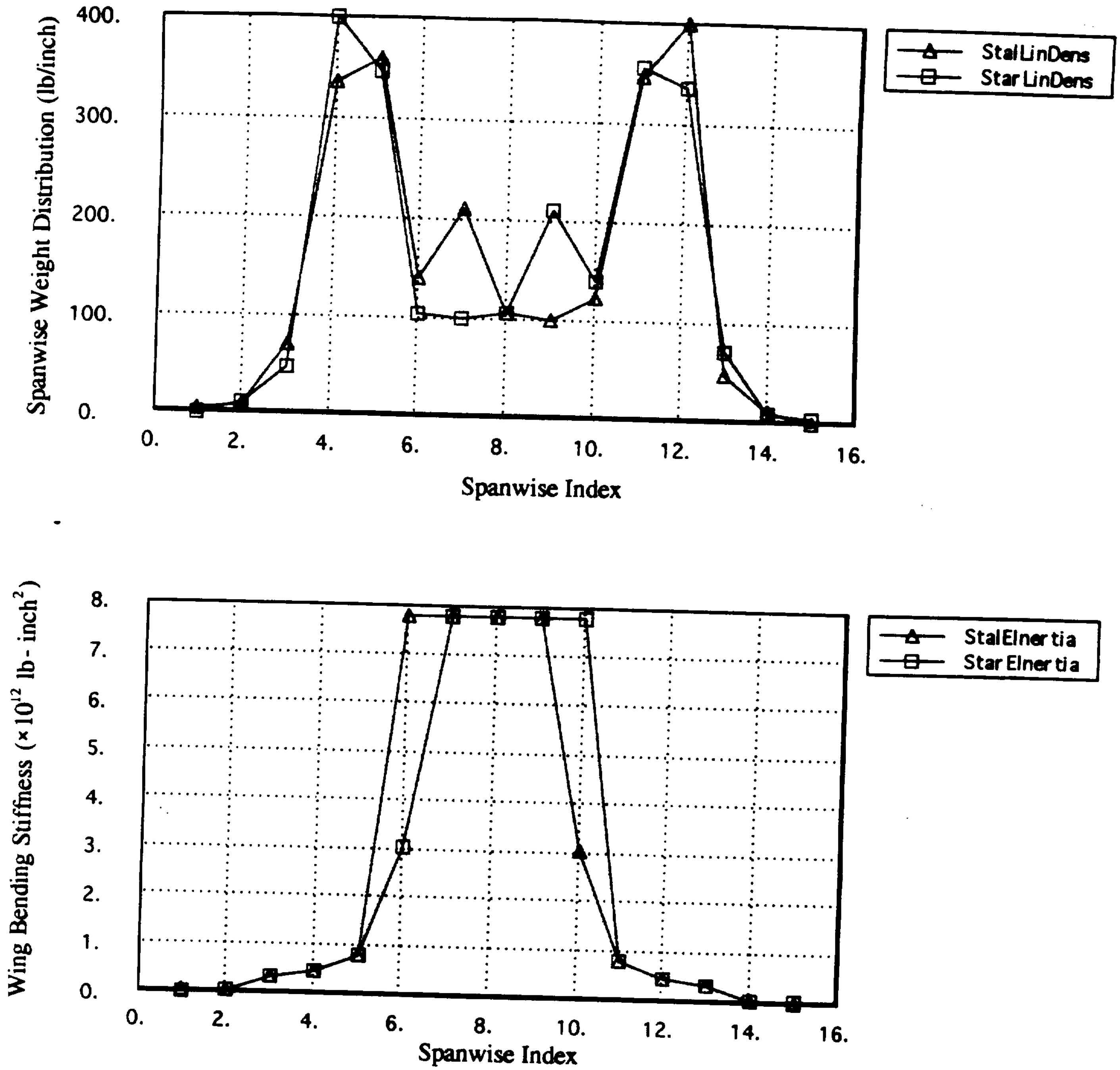


Figure 5 Wing weight distribution and bending stiffness. Note that the wing is heaviest at the location of the fuel tanks (between stations 4-5 and 11-12), outboard of the landing gear, and outboard of the stiffest part of the wing.

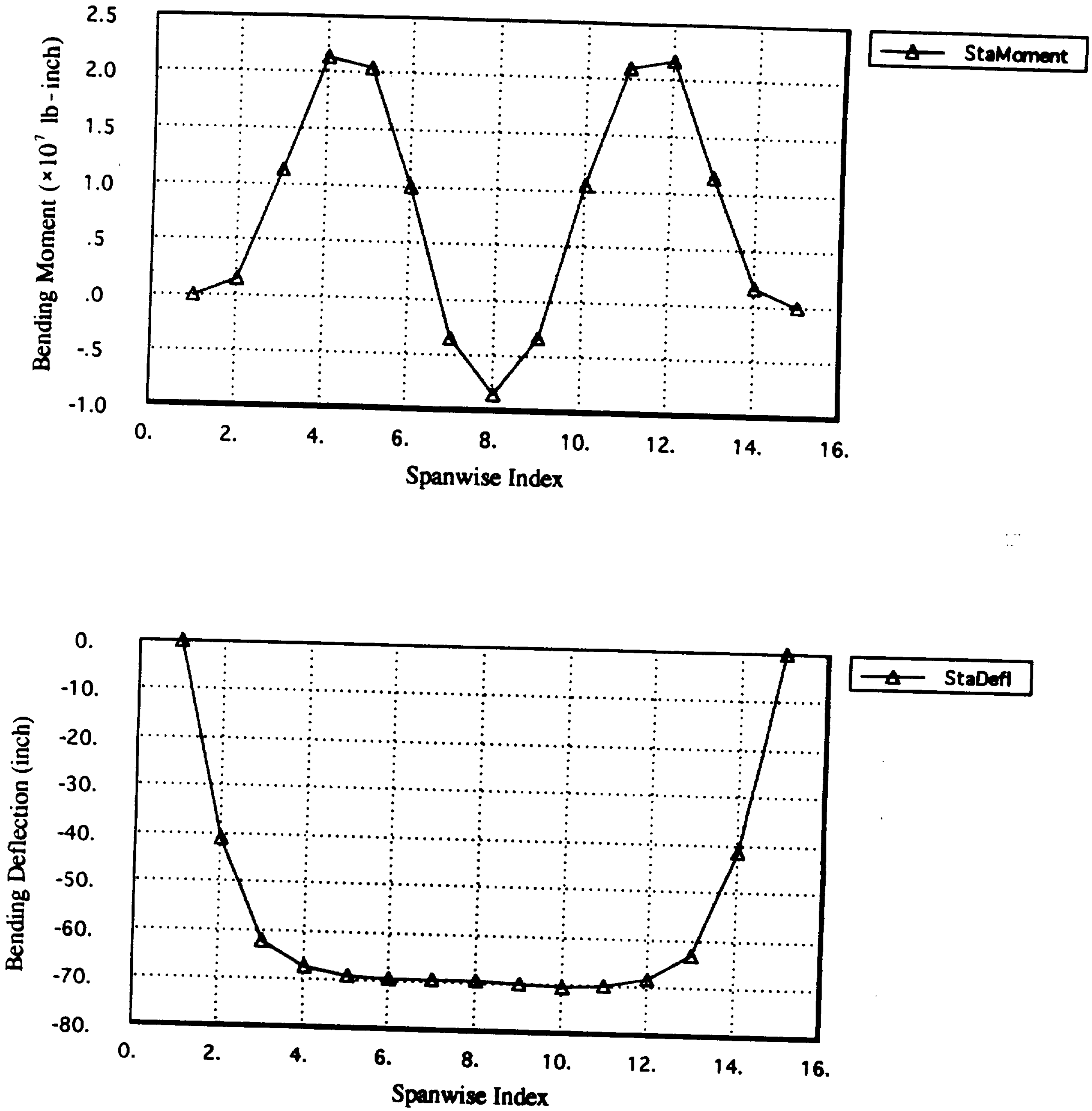
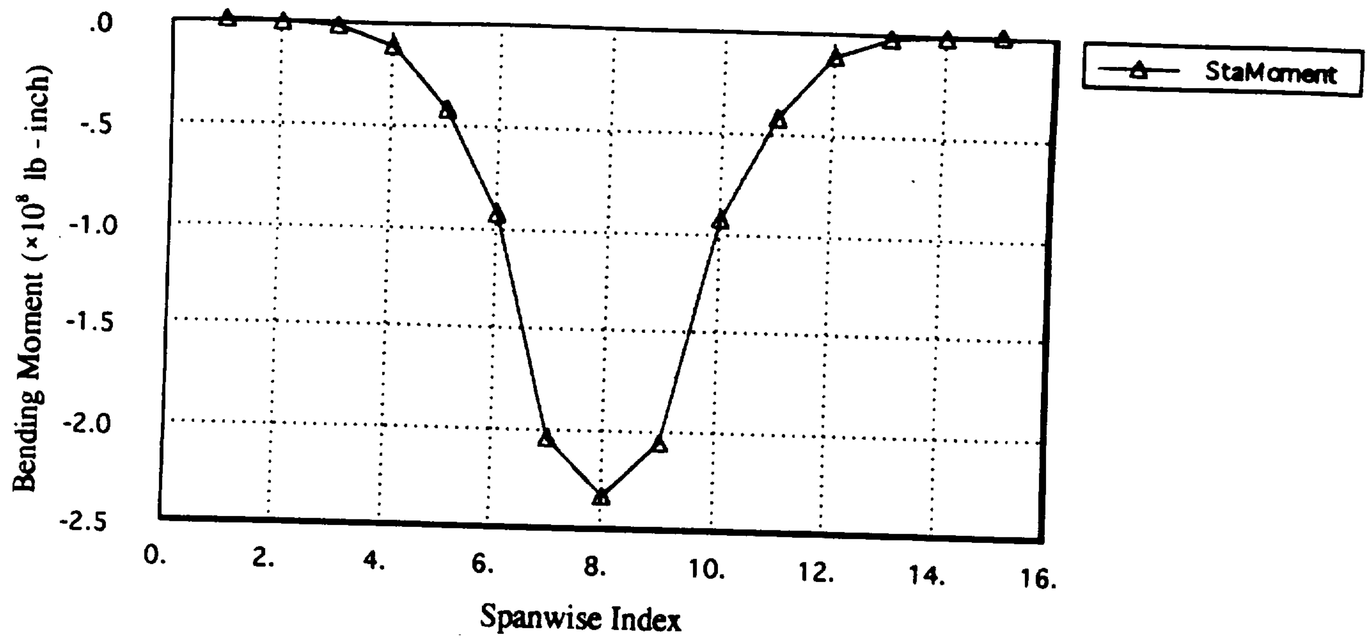


Figure 6 Bending moment and deflection for the wing subjected to 1-g flight loads. The lift distribution is assumed to be elliptical with a small anti-symmetric correction to cancel the non-symmetric weight distribution.



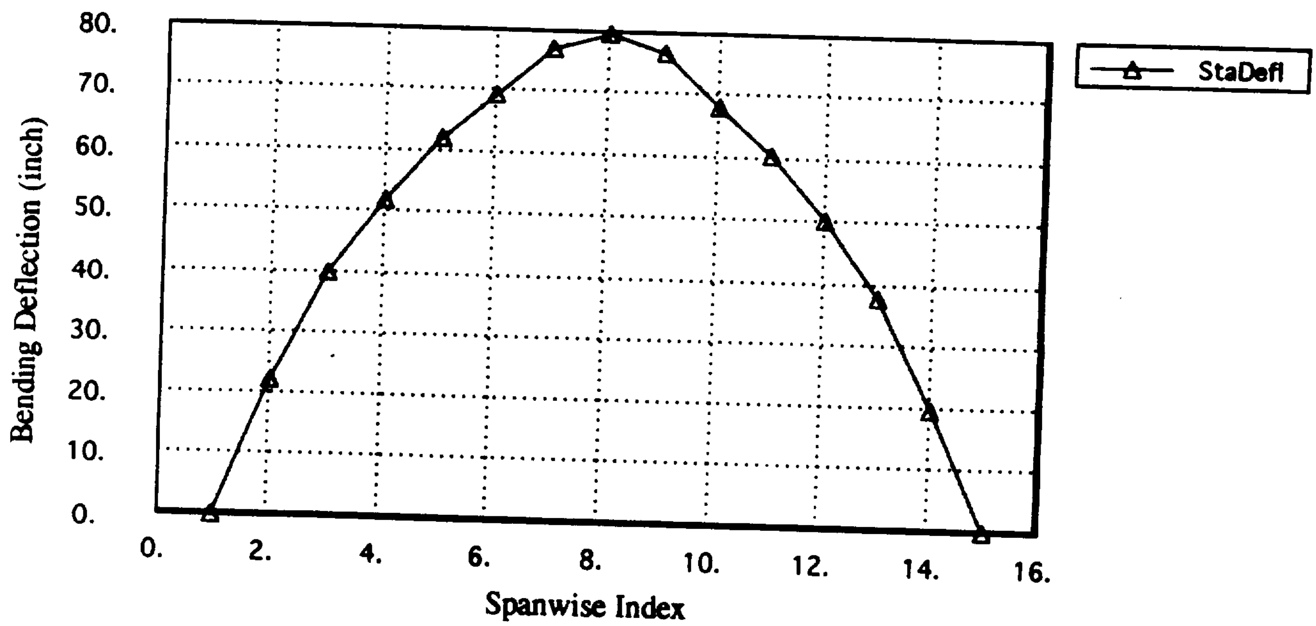


Figure 7 Bending moment and deflection with the wing subjected to 1-g ground loads. The wing is supported soley by its landing gear, located quite far inboard.

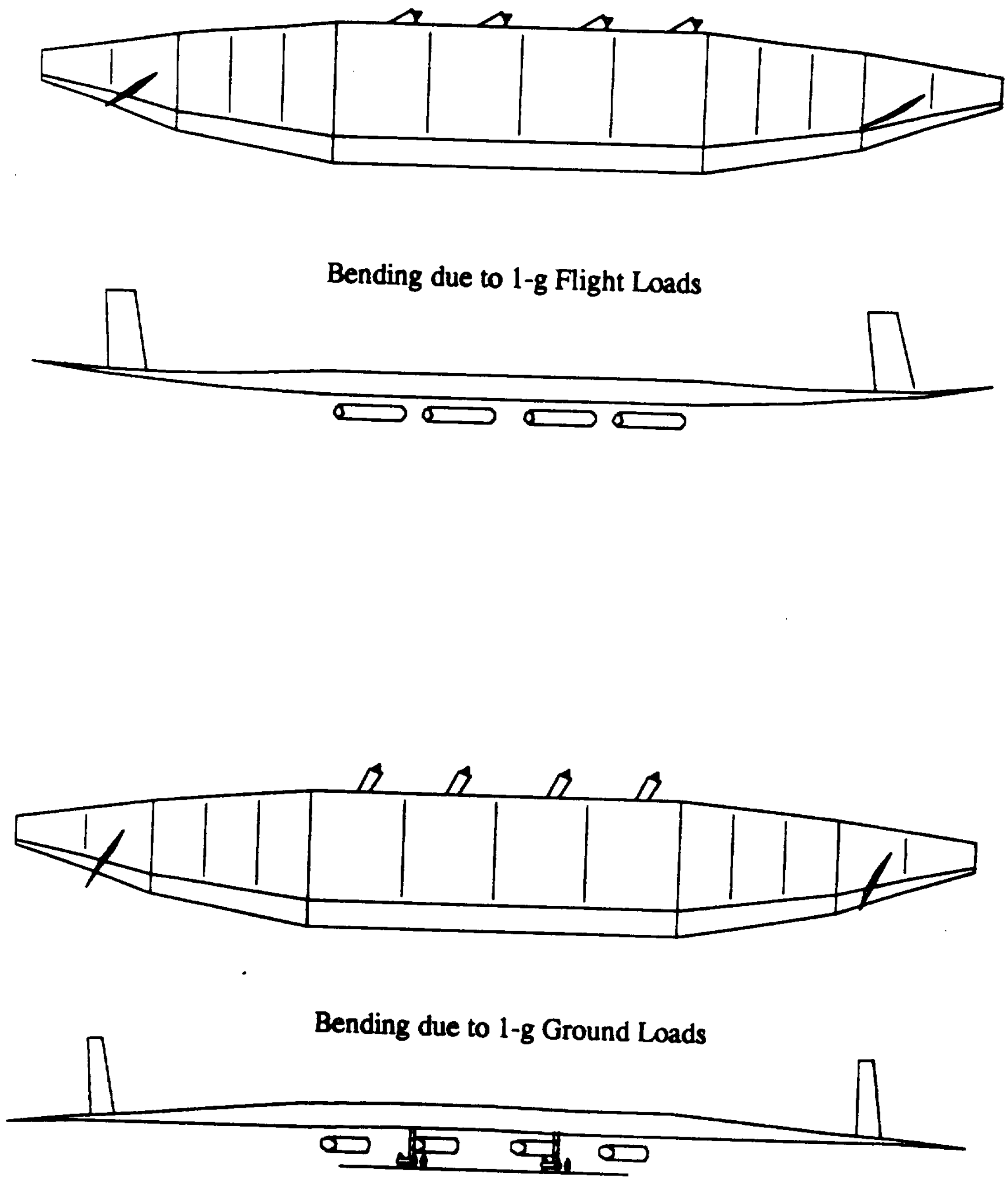


Figure 8 Graphical display showing the magnitude of bending deflections under 1-g flight and ground loads, relative to the airplane dimensions.

	Weight (lb)	CG loc (inch)
Structure	112,345	
Foward Door Penalty	1,252	-119.4
Rear Door Penalty	3,441	205.6
Pressure Ribs	2,642	43.1
Wing Hinges	6,000	-31.0
Engine Attachment	2,140	-164.4
Gear Attachment	2,196	51.0
Fasteners	229	43.1
Fuel	35,970	0.0
Unuseable Fuel	695	0.0
Fuel System	5,461	-14.4
Inlets	4,000	-314.4
Cowlings	5,960	-174.4
Engine Supports	10,000	-149.4
Engines	37,840	-164.4
Engine Accessories	520	-169.4
Engine Controls	330	-197.4
Engine Starting System	240	-214.4
Nozzles	7,520	-39.4
Oil	278	-164.4
APU	2,091	-164.4
Instruments	2,060	-164.4
Surface Controls	7,602	325.6
Hydraulics	5,347	-143.4
Electrical	8,590	-64.4
Electronics	2,440	-77.4
Flight Provisions	900	-174.4
Passenger Accom	29,580	60.6
Cargo Compartment	10,000	-40.4
Emergency Equipment	1,879	35.6
ECS	15,850	-104.4
Icing Protection	880	-184.4
Exterior Markings	264	85.6
Custom Options	2,957	-64.4
Landing Gear	35,050	51.0
Fins	5,290	110.6
Flight Crew	340	-104.4
Cabin Crew	2,156	139.4
Crew Baggage	627	-54.4
Crew Provisions	100	-54.4
Oxygen	277	60.6
Food	3,634	60.6
Life Rafts	2,741	58.1
Life Jackets	924	58.1
Water	1,448	60.6
Lav Fluid	434	-104.4
Passenger Service	1,372	60.6
Galley	4,464	-104.4
Total:	**692,223**	**1.7**

Table 1 Weight breakdown of the baseline airplane. Structural weight is calculated by the program; all others are treated as fixed inputs.