Analytical Comparison of Two Wing Structures for Mach 5 Cruise Airplanes

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Mach 5 cruise airplane studies at the NASA Langley Research Center have identified technologies requiring improvements in the current art to provide adequate cruise range. As part of the overall study, this paper presents analytical results and a comparison of two titanium wing structures each designed for equal stiffness. The first structure is similar to that of the YF-12/SR-71 series airplane, but uprated by use of a better titanium alloy. It consists of spot-welded, corrugated-core sandwich panels having beaded skins, designed to minimize thermal stress, attached to multiple spars and ribs having flat z-stiffened shear webs. The second structure consists of diffusion-bonded honeycomb-core sandwich panels, designed to withstand the thermal stresses, attached to multiple spars and ribs having sine-wave stiffened shear webs. Both structures of titanium (6-2-4-2) alloy were analyzed for the thermostructural loads imposed by flight at Mach 5. The results indicate that with an insulated, integral tank fuselage, the lower surface of the wing must be insulated to satisfy the creep requirements for a 2500-h life at Mach 5; and for equal stiffness, the honeycomb-core sandwich structure is potentially 23% lighter than the corrugation-stiffened beaded skin structure.

Nomenclature

E	= modulus of elasticity
h	= panel height
l	= panel length
N	= compressive load intensity
q	= heat flow
$\bar{t}$	= equivalent skin thickness
T	= temperature
ν	= Poisson's ratio
ρ	= density
σ	= stress

Subscripts

aw	= adiabatic wall
cond	= conduction
conv	= convection
rad	= radiation

Introduction

MACH 5 cruise research at the NASA Langley Research Center includes aerodynamics, propulsion, and structures. The study of structures includes the propulsion system, fuselage, and wings. Various studies have shown that the achievement of adequate range is dependent largely on a low structural mass fraction.

This paper presents results of a study of two wing structure configurations for Mach 5 airplanes. The study commenced with an investigation of an uprated version (6-2-4-2 titanium replacing B-120 titanium) of the YF-12/SR-71 wing structure. The B-120 titanium structure represents the current art of high-speed airplane wing structures and an excellent data base of analyses and tests exists.[1] The YF-12 wing structure was designed about 20 years ago when the analytical methods for calculating thermal stresses were limited. The structure of the YF-12 was, therefore, designed to minimize thermal stress. This structural configuration consists of chordwise beaded panels stiffened by chordwise corrugations. These panels prevent biaxial thermal stress within the panel because of the low extensional stiffness in the spanwise direction. To carry spanwise bending loads, heavy spar caps are required and the rear spar is exceptionally heavy to carry control surface loads. The rib and spar webs consist of z-stiffened flats sheets.

The second wing structural configuration studied in the present study also used Ti-6242 material but replaced the corrugated-beaded panels with diffusion-bonded honeycomb-core sandwich panels and replaced the z-stiffened shear webs with sine-wave stiffened shear webs.

The scope of this study is limited to the outboard wing section from wing-mounted engine nacelle to wing tip. This section of the YF-12 wing is designed by stiffness requirements rather than material strength requirements. The honeycomb structure was designed to have the same spanwise and chordwise bending and torsional stiffnesses as the uprated YF-12 structure, and these stiffnesses at room temperature are equal to those of the original YF-12 outboard wing section. A structure (honeycomb-core sandwich panels) that is capable of simultaneously supporting spanwise and chordwise loads offers potential for lower weight than the uprated YF-12 structure. However, this type of structure inherently generates higher thermal stresses and for Mach 5 flight; thermal stresses are considerably greater than for Mach 3 flight of the SR-71. Also, the nacelle was assumed to represent a fuselage and the outboard wing section was analyzed for three fuselage designs. These included an empty hot fuselage and two insulated fuselages representing integral tanks for JP and LCH_4 fuel, respectively, which impose higher temperature differences in the structure. Therefore, further study of honeycomb-core sandwich structure was required to determine whether or not it is the better structure for the Mach 5 airplane outboard wing section.

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This paper describes a study Mach 5 airplane using the uprated YF 12 structure and the honeycomb core sandwich structure for the outboard wing section Design criteria are listed and structural sizing thermal analyses ther mostructural analyses and weights for both structures are presented In addition conclusions are given regarding the suitability of the honeycomb core sandwich structure to the outboard wing section of Mach 5 cruise airplanes

Mach 5 Cruise Airplane Configuration

The study airplane configuration is shown in Fig 1 The aircraft is in the 250 000 lb takeoff gross weight class It is about 200 ft long with a 75 ft wing span The wing has a thickness to chord ratio of 2 5% and a planform area of about 3000 ft^2 Several propulsion systems are envisioned including hydrocarbon (JP) and liquid methane (LCH_4) fueled turboramjet engines to provide Mach 5 cruise capability

For the analysis of the wing structure of this class of air craft the YF 12 outboard wing section structural con figuration was used because it represents the current art and an excellent data base exists for analyses and tests on this aircraft The YF 12 outboard wing section geometry shown in Fig 2 is representative of the proposed Mach 5 aircraft outboard wing panel This wing section is integral with a 70 in diam nacelle half and is representative of the wing structure The expected flight conditions are shown in Fig 3 In addition plots of typical windward surface radiation equilibrium temperatures and adiabatic wall temperatures as functions of Mach number and altitude are shown in Fig 3 Figure 3 also indicates that at Mach 3 the radiation equilibrium temperature for lower surfaces is about 500 F while at Mach 5 the lower surface radiation equilibrium temperature is about 900 F at the cruise flight condition

Description of Outboard Wing Section

The uprated YF 12 outboard wing section structure consists of spot welded corrugation stiffened beaded skin panels as shown in Fig 4 The skin panels are mechanically attached to standoff supports which are integral with the spar caps and the spar caps are adjacent to the inner skin corrugations about 1 in from the outer surface The wing ribs and the front and rear spars form the terminations of the skin panels with a mechanical joint on the outer mold line The shear webs for the spars and ribs are flat panels with z stiffeners All material is 6Al 2Sn 4Zr 2Mo titanium alloy

The ribs and skins support any chordwise bending and the rear spar supports most of the control surface load by spanwise bending Thus the rear spar is exceptionally heavy The outboard wing section has 10 spars on 16 in centers and 5 ribs with centerlines varying from 5 to 30 in as shown in Fig 2 The corrugated beaded skin is relatively ineffective in support of the spanwise loads but reduces the thermally in duced loads by eliminating biaxial skin loading

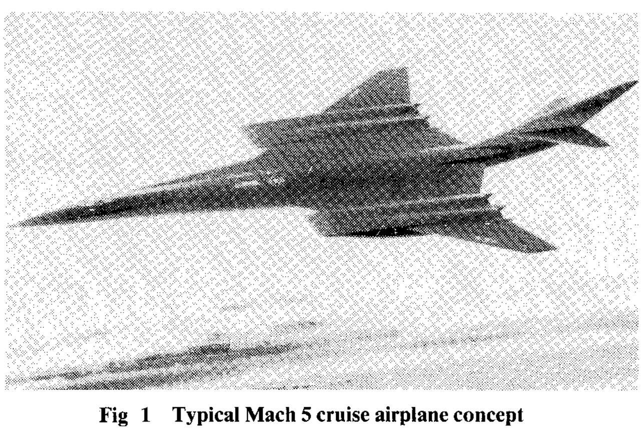

Fig 1 Typical Mach 5 cruise airplane concept

The honeycomb core sandwich wing proposed for the second structure is shown in Fig 5 The titanium core is at tached to the titanium face sheets using a proprietary liquid interface diffusion (LID) bonding procedure [2] LID bonding is required because the currently known braze alloys for titanium honeycomb are unacceptable for use over 500°F and solid state diffusion bonding would require higher tem peratures and pressures than the LID bonding which may crush the honeycomb core The panel closeout members are solid state diffusion bonded to the face sheets and the panels can be either welded or mechanically joined at the spar and rib caps

The ribs and spars are superplastically formed sine wave stiffened webs which require no additional stiffeners The rib and spar caps are solid state diffusion bonded to the webs and the spar caps are much lighter than for the YF 12

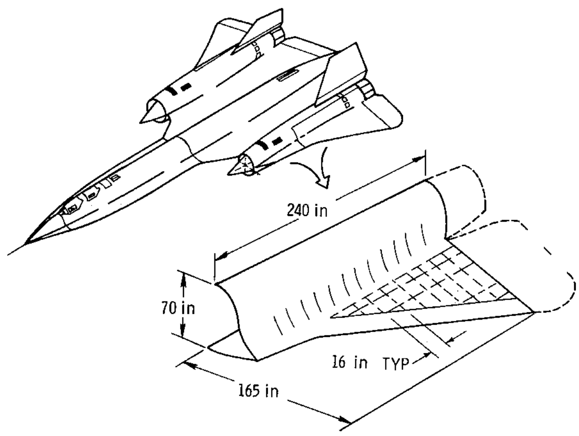

Fig 2 Outboard wing section geometry

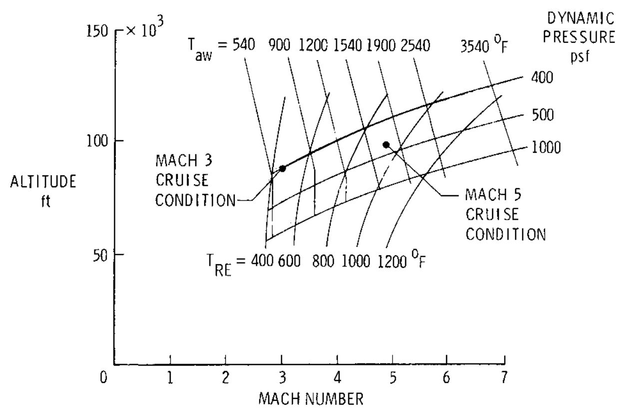

Fig 3 High speed aircraft operating conditions

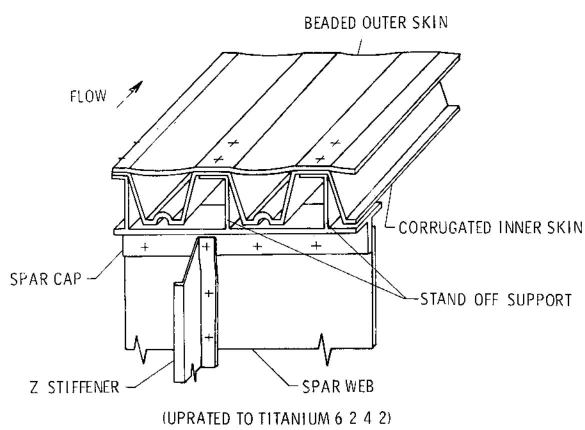

Fig 4 YF 12 wing structure

structure The honeycomb structure was designed to transmit the control surface loads into the main structural box by ribs and by the biaxial strength of the honeycomb panels; thus a heavy rear spar is not needed because the main wing box supports all loads

Structural Design Criteria

Before the analysis can be made certain design criteria must be established For this study these criteria include: a safety factor of 1 5 for airloads; a 2 5 g subsonic maneuver load; a design life of 2500 h with a scatter factor of 4; a total creep strain of 0 2%; a maximum use temperature of 1000 F; and a minimum gage of 0 010 in for the titanium material Also the stiffness of the YF 12 outboard wing section was assumed to be necessary to meet aeroelasticity requirements The 6Al 2Sn 4Zr 2Mo titanium alloy material properties were taken from Refs 3 and 4

Structural Sizing

To compare the two structures a finite element model (Fig 6) representing the outboard wing section structure was generated The model of the uprated YF 12 structure was analyzed using the Engineering Analysis Language (EAL) system[5] of computer programs The EAL system is available from Engineering Information Systems Incorporated San Jose California The model was refined until the experimentally determined room temperature stiffness and weights presented in Ref 1 were matched This required that the model incorporate details such as doublers around cutouts and excess material used for joints and brackets for mounting nonstructural subsystems The resulting model contained 370 nodes over 1600 elements and 1000 degrees of freedom The wing has four nodal points through its thickness to represent the locus of the inner and outer surfaces of the skins. These nodes are a uniform 1 0 in apart on the upper and lower surfaces The structural model was cantilever supported at the vertical centerline plane of the nacelle and two loads acting upward were applied—one load at each end of the outer rib as shown in Fig 6 These loads induced spanwise and chordwise bending and torsion in the wing structure and were used to determine the stiffness of the structure The honeycomb structure was sized using the same model and loads so that the honeycomb structure had the same room temperature stiffness as the uprated YF 12 structural model

The model complexity for both concepts included the nonisotropic properties of the various structural elements. For example the sine wave shear webs have a lower shear modulus as the modulus of elasticity is only 4/9 the modulus of an equivalent flat shear web Figure 7 shows the modeling simulation for a sine wave web and a honeycomb core The nonisotropic properties of the uprated YF 12 corrugated beaded skin panels were modeled in a similar fashion

Structural Analysis—Aeroinertial Loads

Several analyses using the uprated YF 12 structure and the honeycomb structure were performed These analyses included a 2 5 g limit load maneuver a 1 0 g cruise airload and various thermal load conditions with and without airloads However prior to performing the structural analyses material and structural allowables for the various elements based on failure modes were established

At room temperature the ultimate tensile strength of the 6Al 2Sn 4Zr 2Mo titanium alloy is 155 000 psi the yield strength is 140 000 psi and the ultimate shear strength is 93 000 psi At 900 F the allowable creep strength as seen in Fig 8 is 24,000 psi [3] This allowable is based on 0 2% creep in 2500 h at 900 F An elastic modulus of $16\ 5\times10^{6}$ psi was used at all temperatures The buckling strength of the structurally efficient honeycomb core sandwich panels at the ultimate airload (2 5g limit load times the 1 5 factor of safety) ranges from a load index of $1\ 5\times10^{-6}$ to $1\ 0\times10^{-5}$ (N=500

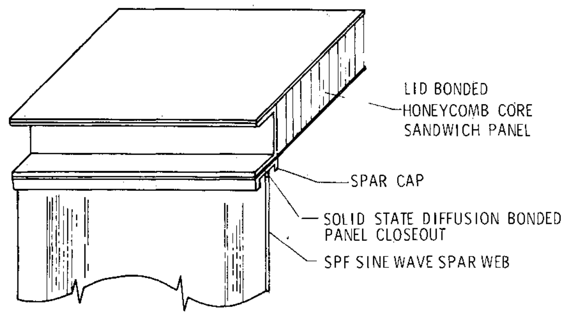

Fig 5 Honeycomb-core sandwich wing structure

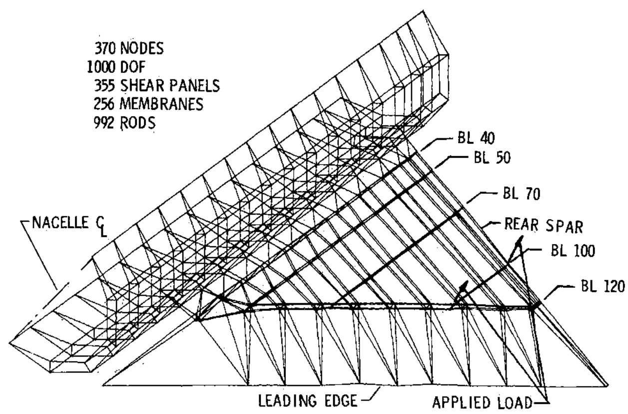

Fig 6 Finite element model of wing structure

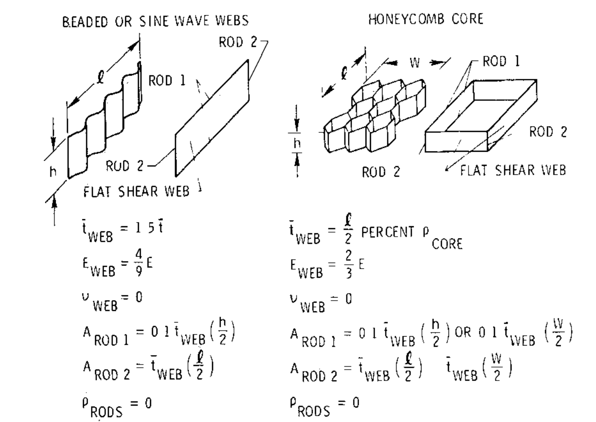

Fig 7 Sine wave web and honeycomb core structural simulation

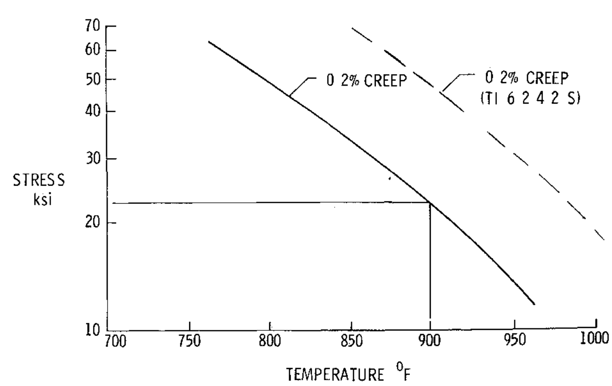

Fig 8 Allowable creep strength for 6 2 4 2 titanium for 2500 h exposure

2500 lb/in) as indicated in Fig 9 This figure is a plot of the weight index ($\bar{t}/l$) as a function of the load index (N/lE) wherein for rectangular honeycomb core sandwich panels the value of l is the shorter edge length regardless of the load direction Consequently each honeycomb panel must be evaluated for its ability to support the ultimate airload Moreover compressive thermal stresses discussed later may exceed the buckling strength of the honeycomb panels thus the thermally induced loads also must be considered To determine the magnitude of thermal stresses transient heating analyses were performed to obtain temperatures of the various structural elements

Thermal Analysis

The primary concern with high speed airplane structures is thermally induced loads The high speed flight environment imposes severe temperatures as shown in Fig 3 and results in large temperature variations within the structure which cause thermal stress The analyses of these thermally induced loads require a rigorous analysis which was not available when the YF 12 structure was designed For the present analysis the transient heating code of Ref 6 was used with the two dimensional model containing 26 elements shown in Fig 10 The specific model shown in Fig 10 represents the honeycomb core sandwich panel face sheets and core on the upper and lower surfaces of the wing The honeycomb core panels are connected with members representing the spar or rib webs and caps The air gap between the upper and lower surfaces is modeled also

The trajectory shown in Fig 11 was used as input to the transient heating code and the resulting thermal histories for a point 100 in aft of the leading edge are depicted in Fig 12 These temperatures were assumed to be uniform over each surface for the analysis The equilibrium temperatures during the cruise portion of a Mach 5 flight are shown to be a maximum of 900 F for the outer skin on the lower surface and a maximum temperature of about 600 F for the outer skin on the upper surface Thus a 300 F temperature difference exists for an extended period between the upper and lower wing surfaces Moreover the nacelle would have similar temperature profiles if it were only exposed to aerodynamic heating

Assuming the nacelle to represent a fuselage it could be a hot structure containing a nonintegral fuel tank or it could be an insulated integral fuel tank in which case the structure would remain at the fuel temperature due to the large heat sink capacity of the fuel As shown in Fig 12 an integral tank fuselage would be about 70 F for JP fuel and about -240 F for liquid methane fuel which is below the temperature scale on Fig 12 The temperature differences between the hot wing and the colder integral tank fuselage structures are much greater than the difference between the upper and lower wing surfaces and are the principal sources of thermal stresses Also, the maximum temperature difference between the upper and lower wing surfaces does not occur during cruise but is maximized at 650 F during the climb portion of the flight (900 s) as shown in Fig 12 All three fuselage configurations were analyzed

Structural Analysis—Aerothermal Loads

The structural temperatures Fig 12 were used as input for the structural analysis which used the EAL program and the finite element model shown in Fig 6

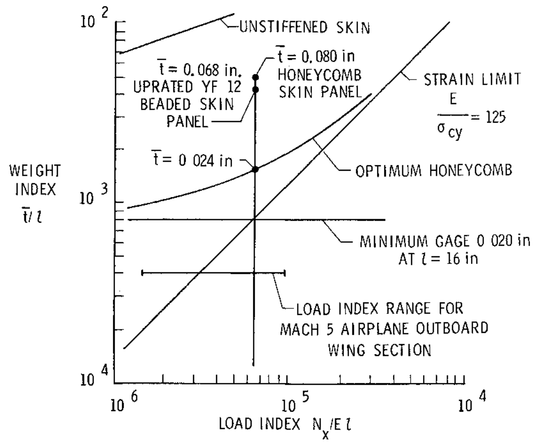

Fig 9 Weight index as a function of load index

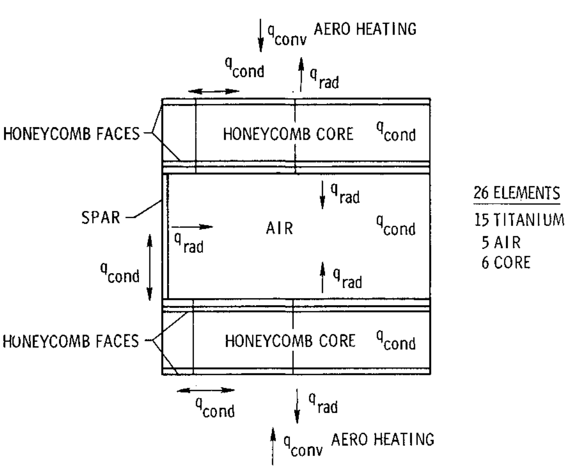

Fig 10 Thermal model of wing structure

Table 1 Maximum thermal stress in uninsulated Mach 5 wing structures

Concept		Flight condition	Maximum skin stress psi	Skin panel temperature F	Allowable stress psi
Hot fuselage	Beaded skin	Ascent	$-29\,300$	840	88 000
		Cruise	15 500	640	93 000
	Honeycomb skin	Ascent	$-45\,630$	840	88 000
		Cruise	13 210	640	93 000
JP fuselage 100 F	Beaded skin	Ascent	$-51\,700$	840	88 000
		Cruise	$-48\,000$	900	24 000[a]
	Honeycomb skin	Ascent	$-57\,330$	840	88 000
		Cruise	$-38\,160$	900	24 000[a]
LCH_4 fuselage -240 F	Beaded skin	Ascent	$-63\,900$	840	88 000
		Cruise	$-60\,200$	900	24 000[a]
	Honeycomb skin	Ascent	$-65\,990$	840	88 000
		Cruise	$-59{,}970$	900	24,000[a]

[a] Allowable stress for 0 2% creep in 2500 h

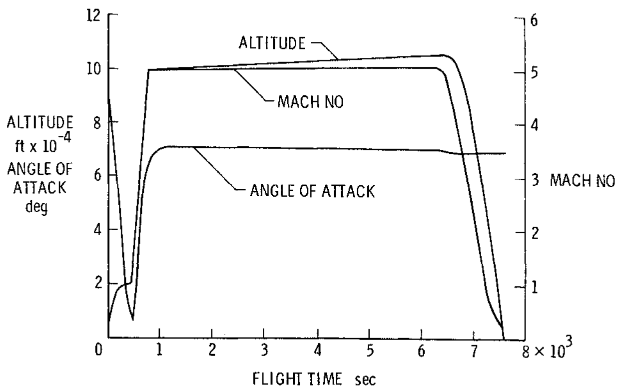

Fig 11 Mach 5 airplane trajectory

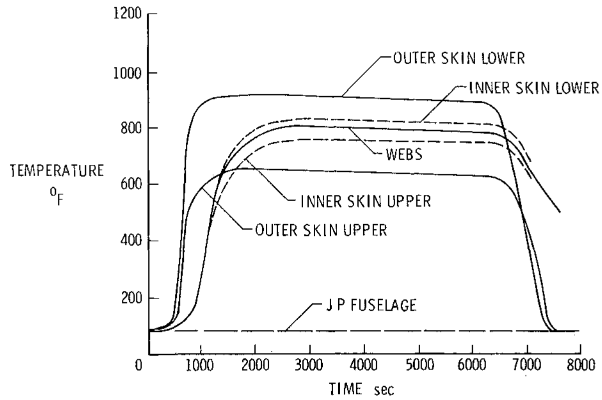

Fig 12 Thermal history of Mach 5 wing structure

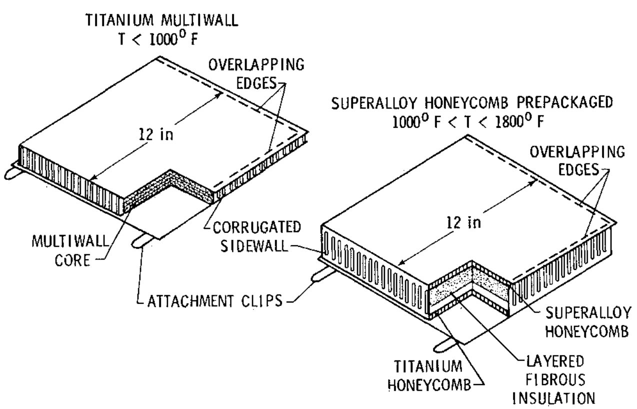

Fig 13 Multiwall TPS concepts

Table 2 Weight summary for Mach 5 outboard wing section structures

Component	Component weights lb Insulated beaded structure	Insulated honeycomb structure
Skins	176 7	171 1
Ribs	78 5	31 8
Spars	205 0	114 0
Leading edge	62 1	62 1
TPS	77 4	77 4
Total	599 7	456 4
Unit weight wetted area, psf	3 48	2 65

The large temperature difference between the wing structure and the integral tank fuselage results in high thermal stresses in the wing fuselage interface Therefore the wing root panels were remodeled and input to the structural model as spanwise beaded panels in an attempt to reduce the local thermal stresses Moreover another approach to reduce the thermal stresses in the wing is the use of external insulation on the lower surface An all titanium multiwall thermal protection system [7] shown in Fig 13 is capable of providing this insulation function An alternate multiwall concept for higher temperature applications is shown also This mechanically attached durable TPS is required only on the lower surface of the aircraft and is described more fully in Refs 7 and 8

Results

Aeroinertial Loads

The ultimate load condition consisted of a 2 5 g subsonic maneuver with the 1 5 factor of safety combined with point loads and moments applied along the rear spar representing the control surface loads This load condition included both aero and inertia loads and produced maximum tensile and compressive stress levels of 50 000 psi in the structure which are well below the material and panel buckling allowables For instance for a $\bar{t}$ of 0 034 in at a compressive stress of 50 000 psi N is 1700 lb/in and as indicated on Fig 9 (for a spar spacing of 16 in) the load index is 6 5×10^{-6} which results in a $\bar{t}$ of 0 024 in to resist buckling for an optimum honeycomb sandwich design However since the wing is stiffness designed the $\bar{t}$ of the honeycomb at this location is 0 080 in thus the stress in the honeycomb skins at ultimate load is only 32 000 psi which is considerably less than the buckling allowable stress Figure 9 shows these results as well as those for the uprated YF 12 structure

The cruise condition loads were also analyzed with the lower 1 0 g hypersonic airloads resulting in proportionally lower maximum stress levels about 13 000 psi, again well below the allowable for buckling and the material even for long exposures at elevated temperatures However this 13 000 psi stress is due to airloads and inertia only; that is no thermal loads were included in this analysis

Thermal loads

The maximum principal thermal stresses for the hot fuselage (considering the nacelle to represent a fuselage) and the integral tank hydrocarbon and liquid methane fuselages are shown in Table 1 The maximum wing skin stresses for each fuselage temperature are shown during ascent and cruise along with the respective temperatures and allowable stress at that time The maximum principal stresses for the insulated fuselages occur in the lower wing panels near the wing fuselage interface where the maximum temperature difference occurs As shown the hot fuselage with the uninsulated wing structures has the lowest thermal stresses which are well below the material or buckling allowable stresses for all conditions However the stresses in the wing panels increase when the fuselage is held at lower temperatures The high temperature differences between the upper and lower wing surfaces during ascent are shown to be acceptable for the hot JP, and liquid methane integral tank fuselages However the stresses generated by the cold fuselages and the hot wing during the cruise portion of the flight while not above the material ultimate strength or panel buckling strength at temperature do exceed the 24 000 psi creep design criterion shown in Fig 8 The beaded wing root panels did not reduce the thermal stress significantly As shown in Fig 8 a reduction in tem perature of 100 F will increase the creep allowable to over 50 000 psi,[2] and also lower the maximum thermal stress in the lower surface However, as indicated in Ref 3 Ti 6242 S alloy has about twice the creep strength of Ti 6242 alloy The use of the Ti 6242 S alloy may eliminate the need for lower surface insulation on the insulated integral tank fuselage with

JP fuel However the integral tank structure with LCH_4 fuel would still require a TPS for the lower surface of the wing

Weights

The weights for the uprated YF 12 wing structure and honeycomb core sandwich structure of the same stiffnesses are compared for a Mach 5 flight profile The TPS required to maintain the lower skin surfaces below 800 F adds 77 lb to the outboard wing panel for both structures This increases the unit weight of the uprated YF 12 structure and the honeycomb structure by about 20% to 3 48 and 2 65 psf respectively, as shown in Table 2 Consequently the honeycomb core sandwich structure is about 23% lighter than the uprated YF 12 structure for Mach 5 airplane wing structure

Conclusions

A rigorous thermostructural analysis of two structures for a Mach 5 airplane wing section was conducted using a large finite element model and the EAL structural analysis code The results of this analysis show that thermal loads are the dominant forces and both a corrugated beaded skin structure and a honeycomb core sandwich structure of titanium alloy are not stressed beyond the yield strength during cruise at Mach 5 The honeycomb sandwich structure and the corrugated beaded skin structure of Ti 6242 alloy, without insulation on the lower surface of the wing are suitable for the outboard wing section of a Mach 5 cruise airplane that has a hot fuselage structure (nonintegral tanks) However, with insulated integral tank fuselage structures the lower surface panels of the wing require a thermal protection system to maintain the titanium (Ti 6242) temperature below 800 F to prevent excessive creep The Ti 6242 S alloy which has twice the creep strength of the Ti 6242 alloy may permit the use of an uninsulated wing for an integral fuselage tank for JP fuel but not for LCH_4 fuel The insulated honeycomb sandwich structure is 23% lighter than an insulated corrugated beaded skin structure for the same stiffness

If an optimum honeycomb core sandwich structure were used that was sized for strength it would be 70% lighter than the stiffness designed honeycomb structure of this study Thus the stiffness requirement used for this study requires further justification The honeycomb sandwich structure is attractive for high speed cruise airplanes because it also provides a smooth aerodynamic surface The liquid interface diffusion bonded honeycomb core sandwich panels with superplastically formed diffusion bonded and welded (as required) ribs and spars may reduce fabrication costs because of the lower number of parts and the elimination of mechanical fasteners Therefore, technology developments are warranted to determine whether or not liquid interface diffusion bonded honeycomb core sandwich structures of 6A1 2Sn 4Zr 2Mo S titanium alloy can be fabricated and provide adequate strength and life

References

[1] NASA YF 12 Flight Loads Program NASA TMX 3061 May 1974

[2] Handbook for Rohr Bond Sandwich Design Rohr Industries Inc Chula Vista Calif 1976

[3] Kaneko R S Ti 6A1 2Sn 4Zr 2Mo Structural Development NASA CR 166006 Oct 1982

[4] Aerospace Structural Metals Handbook, U S Department of Defense Dec 1978

[5] EISI/Spar Reference Manual Engineering Information Systems Inc 1979

[6] Garrett, L B and Pitts J I A General Transient Heat Transfer Computer Program for Thermally Thick Walls NASA TMX 2058 Aug 1970

[7] Shideler J L et al Multiwall TPS—An Emerging Technology NASA TM 83133 May 1981

[8] Hays D , An Assessment of Alternate TPS for the Space Shuttle Orbiter NASA CR 165790 Feb 1982