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DESIGN AND VERIFICATION PHILOSOPHIES FOR HIGH PERFORMANCE AEROSPACE VEHICLE STRUCTURES UNDER COMBINED MECHANICAL AND THERMAL LOADING

Dr. Uwe L. BERKES

European Space Agency
P.O. Box 299, 2200 AG Noordwijk, The Netherlands

Abstract

The design of high performance aircraft structures is driven mainly by the sustained aerodynamic heating during high-speed flight. An extended dimensioning and verification philosophy is required for the airframe structure design of these aircraft, which adequately considers the combination of the mechanical loads and of the thermal loads. The very sensitive design of these vehicle shows that if a marginal design philosophy has been chosen, the design may become unfeasible, because of too a high structure mass, or because a sound verification becomes virtually impossible to achieve.

Two basic philosophies exist for combination of the thermal environment to the mechanical environment:

- By applying the Safety-Factor on the induced thermal loads.
- By applying the Safety-Factor on the heat fluxes or performance parameters.

Computations have been carried out for both design philosophies, based on flight conditions for re-entry vehicle. Three types of structures have been considered for comparison of the efficiency: Aluminium fuselage structure covered by a thermal insulation system, Titanium interface structures and 3-D Carbon/Carbon load carrying hot-structures. The most favourable design philosophy is outlined for each structure. Buckling phenomena due to combined thermal and mechanical loading are discussed. The design philosophies are further discussed with respect to verification testing.

Design Philosophies for Combined Mechanical and Thermal Loading of Structures

Historical Outline

First aircraft which required to consider the thermal environment in combination with the mechanical environment have been designed such as to avoid major thermal stress built up in the structure [1]. This has been achieved by implementing corrugated skins, which allow for the thermally induced expansion of the wing structure to yield a virtually thermal stress-free condition perpendicular to the corrugation. However, this requires the implementation of heavy spars to transfer the loads of the engines and of the landing gear into the fuselage. As a consequence, these structures cope with the thermal loads, but are not mass efficient.

Due to the severe and transient thermal load conditions, re-entry vehicles require to consider the combination of the mechanical and of the thermal environment. “Cold” structures have been chosen in previous designs, covered by thermal insulation systems. Combination of the mechanical and of the thermal environment has been accounted for by an extended Safety-Factor philosophy, which considers the induced thermal loads by multiplying them with a specific Safety-Factor and then by adding these loads to the mechanical ones [3].

Nowadays supersonic and hypersonic aircraft design relies on a high ratio of payload mass to structure mass, which cannot be achieved by the structural design principles, previously described. Airframe structures of these vehicle must be able to cope with the mechanical and the thermal effects at the same time and the design philosophy chosen must allow for an adequate verification of the design.

Safety-Factor Philosophy for Aerospace Structure

The basis for the structure design philosophy is to cover for uncertainties in order to assure the “safety” of the structure during its nominal and off-nominal operations. This is achieved by multiplying the limit load conditions by a Safety-Factor to yield the ultimate design conditions:

$$\sigma_{ult.} = J \ \sigma_{lim.}$$

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Element	Safety-Factor		
	Yield	Ultimate	Proof
Airframe	1.0 -1.1	1.4 -1.5	1.0 – 1.2
Pressurized Structure		1.5	2.0

TABLE 1 – Major Safety Factors for aerospace vehicle structure design [2, 5, 8, 9]

This Safety-Factor intends to cover the following uncertainties of the design and of the operations:

- Uncertainties in the estimation of loads
- Inaccuracies arising from the analysis due to idealization of the real structure
- Variations of the material properties
- Inaccuracies when establishing the statistical evaluation of the material properties
- Deterioration of the structure during service life
- Variations with respect to the built standard

The classical Safety-Factor philosophy is based on experiences made over a long time and a set of Safety-Factors emerged from design experience, such as outlined in table 1. In addition to these, specific factors are used to account for design parameters, which impact the safety of the vehicle.

The mainstay of the classical Safety-Factor philosophy accounts only for mechanical loads. A combination of mechanical and of thermal loads requires an extension of this philosophy, described hereafter.

Combined Mechanical and Thermal Design Philosophies

The thermal loads are induced into the airframe by the aerothermal conditions of high speed flight. Thermal fluxes are strongly dependant on: Speed, angle of attack (AoA), atmospheric density being the major parameters. They are split up into outer and inner radiative and structure conductive parts, of which the conductive part induces the heating of the structure and thus the thermal stresses, figure 1.

Two basic philosophies exist for considering the thermal loads together with the mechanical loads:

- By applying the Safety-Factor on the induced thermal loads and then considering them in combination with the mechanical loads. Herein referred to as the indirect case.
- By applying the Safety-Factor on the heat fluxes and then considering the resulting thermal loads in combination with the mechanical loads. Herein referred to as the direct case.

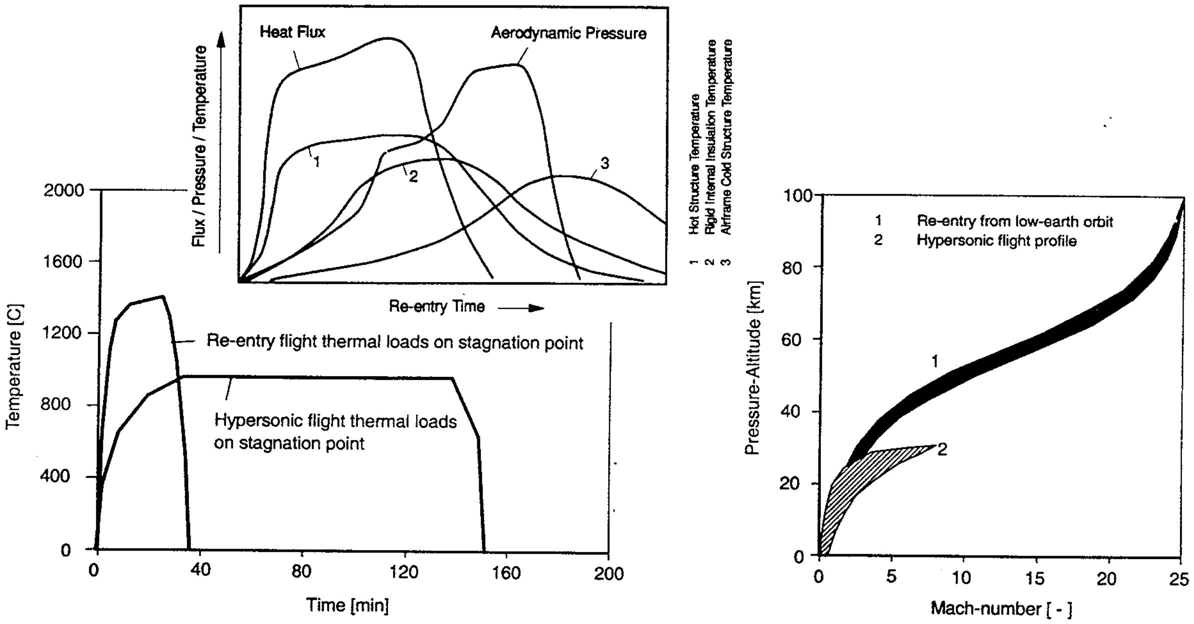
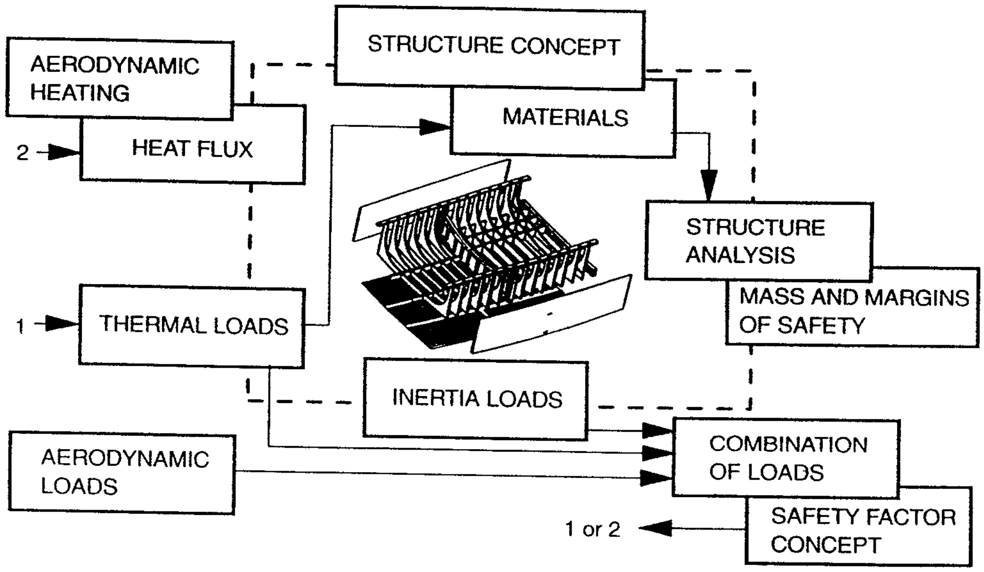


FIGURE 1 – Thermal environment during high-speed flight – Trajectories and thermal conditions [6, 10]



1) Safety-Factor concept with thermal Safety-Factor applied on the thermal loads
2) Safety-Factor concept with thermal Safety-Factor applied on the external heat fluxes

FIGURE 2 – Design cycle for aircraft structures subjected to combined mechanical and thermal loads

Figure 2 presents the structure design cycle and shows how both philosophies act with respect to the elements of the aircraft design.

The first philosophy has as a major advantage a constant Safety-Factor for each of the mechanical and of the thermal loads all over the structure. Its major disadvantage is the need for adaptation of the external heat fluxes during qualification testing or numerical simulations, to reach the specified induced thermal load levels in the structure.

The second philosophy's major advantage is the easy verification by testing and simulation, since variations are applied on the external heat fluxes or on the major performance parameters. However, two ultimate load cases have to be considered, one for mechanical ultimate conditions and one for thermal ultimate conditions. Since thermal loads depend on the local geometry and on local thermal properties of the structure, the thermal load variations are not constant. Thus, the induced Safety-Factor on thermal loads is not constant either.

However, both philosophies have to consider the dependency of the material properties with temperature and the thermal ageing, which itself is a function of the mission profile and life cycle of the aircraft.

Design Philosophy for Combination of Mechanical and Thermal Loads - Indirect Thermal Case -

Two loadcases are to be considered when analyzing the structure load state with the Safety-Factor philosophy:

Limit Load Case:

$$\sigma_{mech.\text{-}lim.} + \sigma_{therm.\text{-}lim.} \leq R_{lim.(lim.\text{-}temp.)}$$

Ultimate Load Case:

$$J_{mech.}\,\sigma_{mech.\text{-}lim.} + J_{therm.}\,\sigma_{therm.\text{-}lim.} \leq R_{ult.(lim.\text{-}temp.)}$$

These two structure design conditions can be transformed into a dimensionless form:

Limit Load Case:

$$\sigma_{mech.\text{-}lim.} / R_{ult.(lim.\text{-}temp.)} + \sigma_{therm.\text{-}lim.} / R_{ult.(lim.\text{-}temp.)} \leq R_{lim.(lim.\text{-}temp.)} / R_{ult.(lim.\text{-}temp.)}$$

Ultimate Load Case:

$$J_{mech.}\,\sigma_{mech.\text{-}lim.} / R_{ult.(lim.\text{-}temp.)} + J_{therm.}\,\sigma_{therm.\text{-}lim.} / R_{ult.(lim.\text{-}temp.)} \leq 1$$

For the special case: $J_{mech.} = J_{therm.} = J$:

$$\sigma_{mech.\text{-}lim.} / R_{ult.(lim.\text{-}temp.)} + \\ \sigma_{therm.\text{-}lim.} / R_{ult.(lim.\text{-}temp.)} \leq 1/J$$

With the different terms referring to:

$\sigma_{mech.\text{-}lim.} / R_{ult.(lim.\text{-}temp.)}$

→ ratio of mechanical loads to ultimate material condition

$\sigma_{therm.\text{-}lim.} / R_{ult.(lim.\text{-}temp.)}$

→ ratio of thermal loads to ultimate material condition

$R_{lim.(lim.\text{-}temp.)} / R_{ult.(lim.\text{-}temp.)}$

→ material yield/ultimate ratio at limit temperature

The Safety-Factors considered in the following computations are $J_{mech.} = 1.4$ and $J_{therm.} = 1.4$.

The material yield/ultimate ratio considers effects such as ageing of the material and the reduction of material properties at limit temperatures. This is thus a major driving parameter, which yields different values depending on the type of aircraft and performance condition.

This philosophy has been validated with the Space Shuttle Design [3]. In addition to the above implementation of the thermal effects, additional Safety-Factors account for the uncertainties of the aerothermal parameters, such as Mach number, angle of attack, Reynolds number and boundary layer conditions.

Design Philosophy for Combination of Mechanical and Thermal Loads - Direct Thermal Case -

As was outlined before, it is straightforward to establish the Safety-Factor on the heat flux, or on the performance parameter, such as speed. In case for heat loads being the designing parameter, the design rules are written in the following form:

Limit load case:

$$\sigma_{mech.\text{-}lim.} + \sigma_{therm.\text{-}lim.} \leq R_{lim.(lim.\text{-}temp.)}$$

Ultimate mechanical case:

$$J_{mech.}\, \sigma_{mech.\text{-}lim.} + \sigma_{therm.\text{-}lim.} \leq R_{ult.(lim.\text{-}temp.)}$$

Ultimate thermal case:

$$\sigma_{mech.\text{-}lim.} + \sigma_{therm.\text{-}ult.} \leq R_{ult.(ult.\text{-}temp.)}$$

with $\sigma_{therm.\text{-}ult.}$ derived from structure loaded with $\phi_{ult.} = J_{therm.\phi}\, \phi_{lim.}$

Again, these design criteria may be transformed into dimensionless form:

Limit load case:

$$\sigma_{mech.\text{-}lim.} / R_{ult.(lim.\text{-}temp.)} + \sigma_{therm.\text{-}lim.} / R_{ult.(lim.\text{-}temp.)} \leq \\ R_{lim.(lim.\text{-}temp.)} / R_{ult.(lim.\text{-}temp.)}$$

Ultimate mechanical load case:

$$J_{mech.}\, \sigma_{mech.\text{-}lim.} / R_{ult.(lim.\text{-}temp.)} + \\ \sigma_{therm.\text{-}lim.} / R_{ult.(lim.\text{-}temp.)} \leq 1$$

Ultimate thermal load case:

$$\sigma_{mech.\text{-}lim.} / R_{ult.(lim.\text{-}temp.)} + \sigma_{therm.\text{-}lim.} / R_{ult.(lim.\text{-}temp.)} \\ \sigma_{therm.\text{-}ult.} / \sigma_{therm.\text{-}lim.} \leq R_{ult.(ult.\text{-}temp.)} / R_{ult.(lim.\text{-}temp.)}$$

With the terms previously not explained:

$\sigma_{therm.\text{-}ult.} / \sigma_{therm.\text{-}lim.}$

→ ratio of ultimate/limit thermal loads

$R_{ult.\ (ult.\text{-}temp.)} / R_{ult.\ (lim.\text{-}temp.)}$

→ ratio of ultimate material properties at ultimate/limit temperatures

The ratio of ultimate to limit thermal loads is a function of the structure design, the thermal properties of the structure and of the thermal properties of the material. In addition, this ratio is a function of the Safety-Factor on thermal fluxes.

The influence of the temperature on the ultimate material properties is again a function of the material itself, but also of the structure design, which drives the ratio between limit and ultimate temperatures and as such, of the Safety-Factor on thermal fluxes.

The Safety-Factors considered in the computations are $J_{mech.} = 1.4$ and $J_{therm.\phi} = 1.5$.

Factorizing Performance Parameters

In the previous design philosophy, the Safety-Factor has been applied on the heat fluxes. However, the heatflux is a function of major performance parameters, such as the vehicle speed.

Applying the Safety-Factor on the speed would lead to the following expression of the design rules:

Limit load case:

$$\sigma_{\text{mech.-lim.}} + \sigma_{\text{therm.-lim.}} \leq R_{\text{lim.(lim.-temp.)}}$$

Ultimate mechanical case:

$$J_{\text{mech.}}\ \sigma_{\text{mech.-lim.}} + \sigma_{\text{therm.-lim.}} \leq R_{\text{ult.(lim.-temp.)}}$$

Ultimate thermal case:

$$\sigma_{\text{mech.-lim.}} + \sigma_{\text{therm.-ult.}} \leq R_{\text{ult.(ult.-temp.)}}$$

with $\sigma_{\text{therm.-ult.}}$ derived from design with

$$V_{\text{ult.}} = J_{\text{vel.}}\ V_{\text{lim.}}$$

The relation between speed and heat flux:

$$\phi_{\text{lim.}} = c_Q\ (\rho/R)^{0.5}\ V^3_{\text{lim.}}$$

Hence, the thermal ultimate condition can be transformed:

$$\sigma_{\text{mech.-lim.}} + \sigma_{\text{therm.-ult.}} \leq R_{\text{ult.(ult.-temp.)}}$$

with $\sigma_{\text{therm.-ult.}}$ derived from design with

$$\phi_{\text{ult.-vel.}} = J_{\text{vel}}\ c_Q\ (\rho/R)^{0.5}\ V^3_{\text{lim.}}$$

Thus, the above presented design rules can be extended in this way allowing to consider major performance parameters.

Consequences of Thermal Loading on Material Behaviour

As was presented in the discussions on the two design philosophies for combined mechanical and thermal loading, an important part of the design rules are the material characteristics, which are a function of the temperature. Two ratios were important in this respect:

$$R_{\text{lim. (lim.-temp.)}} / R_{\text{ult. (lim.-temp.)}}$$

→ material yield/ultimate criterion at limit temperature

$$R_{\text{ult. (ult.-temp.)}} / R_{\text{ult. (lim. -temp.)}}$$

→ ratio of ultimate material properties at ultimate/limit temperatures

In the following examples, four materials are used for comparison of the efficiency of the design philosophies:

- Aluminium alloy Al2024 T62 and T81
- Titanium alloy Ti6Al4V
- 3-D woven Carbon-Carbon

Material data for these materials have been established from well known sources, such as the MIL-Handbook 5, expanded by own test-series, to substantiate the characteristics of each material at higher temperatures. Test-series have been performed with the following test-conditions:

- Aluminium alloys aged with cyclic ageing over 100 hours with 175°C limit and 210°C ultimate temperatures, simulating re-utilization for 30 re-entry trajectories.

- Titanium alloy aged over 100 hours at 400°C limit temperature and 450°C ultimate temperature.

- Carbon-Carbon material has been exposed in larger testseries at limit and ultimate conditions for the material.

Table 2 presents the results of those investigations for the two major ratios of the design philosophies. As can be seen, the Aluminium alloy is sensitive to thermal loading and to thermal ageing. In its state T62, the reduction of the ultimate strength is almost 30% with respect to the same value at limit temperature conditions. In state T81 the reduction is still in the order of 22%. These characteristics describe a temperature sensitive material.

For the Titanium alloy, the reduction of the strength with respect to thermal effect is by far less important.

Material	Ratio of yield/ultimate property at limit temperature $R_{\text{lim. (lim.-temp.)}} / R_{\text{ult. (lim.-temp.)}}$	Ratio of ultimate property at ultimate/limit temperature $R_{\text{ult. (ult.-temp.)}} / R_{\text{ult. (lim. -temp.)}}$
Al 2024 – T62	0.85	0.71
Al 2024 – T81	0.91	0.78
Ti 6 Al 4 V	0.80	0.92
C/C 3-D woven	~ 1	~ 1

TABLE 2 – Material properties of aged materials as a function of the thermal conditions

The reduction is in the order of only 8% of the ultimate tensile strength value.

The Carbon-Carbon 3-D woven ceramic is almost insensitive to thermal effects. Virtually no reduction could have been identified for what concerns the tensile strength although exposed to ageing temperatures above 1600° C. Further to this, its virtually linear behaviour until rupture (ultimate) strength does not allow to distinguish between yield and ultimate criterion. However, this material yields only low tensile strength at ultimate conditions.

Structure Design-Cases for Evaluation of the Efficiency of the Design Philosophies

Aluminium Fuselage Structure Covered by Thermal Insulation System

The structure which has been analyzed and which has been optimized consists of an Aluminium forward fuselage structure of a re-entry vehicle. The structure is a classical frame-stringer-stiffened skin, which is covered on its outside by a thermal protection system. This thermal protection system is made up of a layer of C/SIC tiles with internal multilayer insulation, which are mounted on the Aluminium skin structure by insulation caps, figure 3.

Titanium Interface Structure

The Titanium structure has been implemented in an area were the "hot" structure of the nose-cap or the leading edge has to be connected to the "cold" structure of the fuselage. The structure has to withstand medium level thermal loads and is covered on its outside by a thermal protection system made up of tiles, figure 4.

Carbon-Carbon Nose Cap Structure

This type of structure is a pure "hot" structure, which is load carrying and which is directly facing the high temperature environment of re-entry flight. The material is made up of 3-D woven C/C, figure 5.

Analytical Evaluation

An aerothermodynamic analysis is required for computation of the heat-fluxes considering the entire trajectory, for design- and off-design conditions. In order to limit the size of the whole analysis, the structure thermomechanical analysis has been decoupled from the aerothermal part. Interface and boundary conditions have been properly defined, in order to consider influences of structure thermal heating on the boundary layer heating conditions. For the Aluminium cold-structure, which is covered by thermal insulation systems, heat fluxes on the cold structure have been established by one-dimensional thermal models, in order to reduce the computational efforts otherwise required when considering both structures in one single Finite-Element analysis.The external heat fluxes have been introduced into the thermomechanical analysis together with initial temperature conditions, established from the aerothermal models. The temperature fields on the structures have then been computed considering the boundary conditions and specific thermal features of the structure (radiative and convective effects) and of the materials (conductivity, specific heat capacity). From this

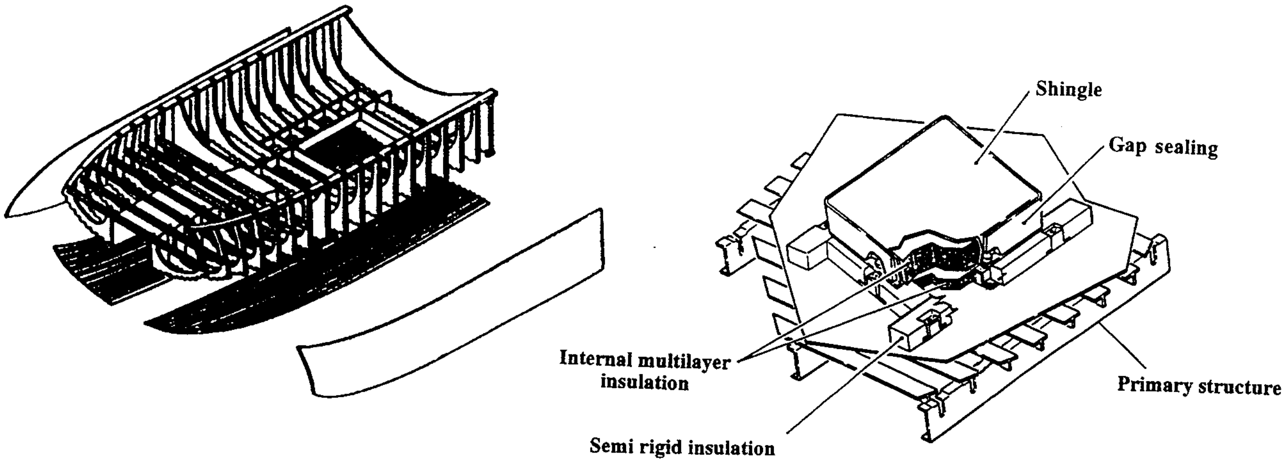


FIGURE 3 – Aluminium fuselage structure covered by thermal insulation system

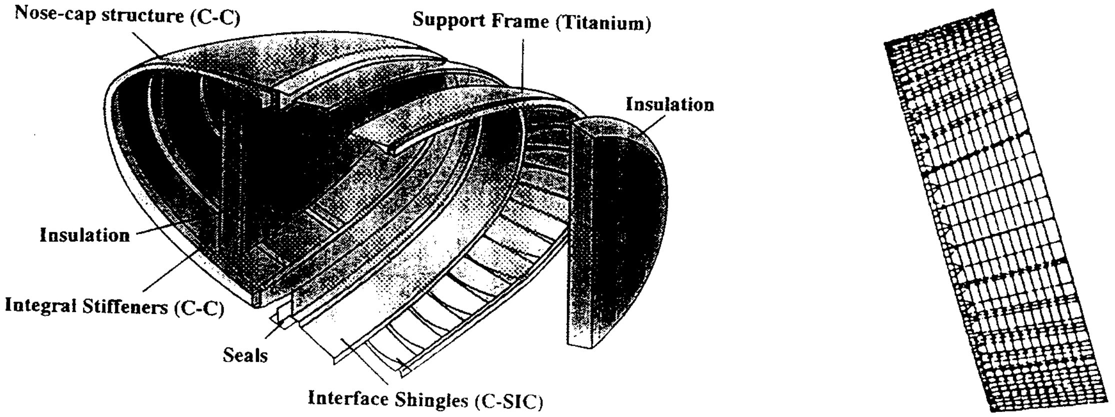


FIGURE 4 – Nose-cap and Titanium interface ring assempbly – Titanium ring Finite-Element model

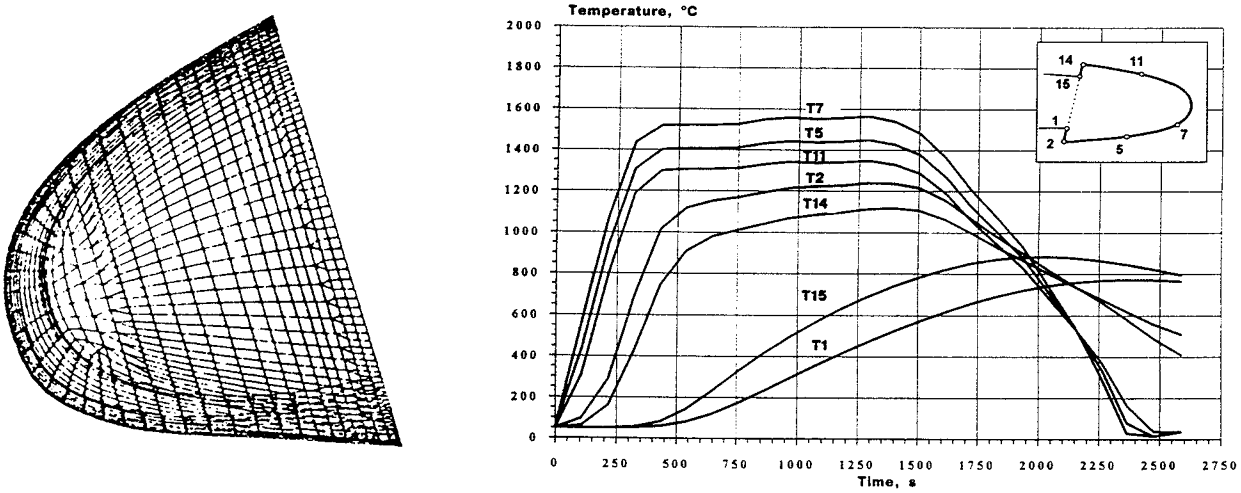


FIGURE 5 – Carbon-Carbon nose-cap structure Finite-Element model and thermal environment

second analysis, the temperature fields on the airframe structure have been established, which are then used in the mechanical analysis.

Since the history of the thermal heating cannot be neglected, it became necessary to consider the development of the heat fluxes and of the temperature fields for the whole trajectory. One computation cycle is required for analyzing the single thermal condition of the indirect design rule. Two computations are required for the direct design rules, one for the mechanical ultimate condition and one for the thermal ultimate condition.

All thermomechanical and aerothermal computations have been carried out using Finite Element Models. For the latter one, a Navier-Stokes code has been used with full thermal and chemical nonlinearities implemented to account for rarefied gas conditions of high altitude re-entry phenomenon.

Table 3 summarizes the results of these computations with respect to the ratio of ultimate/limit thermal loads $\sigma_{therm.-ult.} / \sigma_{therm.-lim.}$. A large variation of this parameter is a sign of a structure which yield:

- Complex temperature distributions
- Large thermal gradients
- Elements with different thermal properties and thermal mass.

Comparison of Results

The following comparison is based on the assumption that both design philosophies yield

Structure	Material	Ratio of structure thermal loads $\sigma_{therm.\text{-}ult.} / \sigma_{therm.\text{-}lim.}$
Forward fuselage structure	Al 2024 – T62	1.12 – 1.37
Forward fuselage skin	Al 2024 – T81	1.09 – 1.29
Interface structure	Ti 6 Al 4 V	1.21
Nose cap structure	C/C 3-D woven	1.218 – 1.221

TABLE 3 – Ratio of ultimate/limit structure thermal loads – Results of computations

similar structural safety, which is assured by the values of the Safety-Factors chosen for both design approaches.

Figures 6 to 9 present the results for each of the structures and for the two design philosophies.

In these figures, the mechanical term of each of the design rules is presented on the x-axis, and the thermal term is presented on the y-axis. Due to the linear behaviour of the design rules, this yields a simple set of lines, which may easily be interpreted. The resulting line of a design rule, which lies on the uppermost right corner, yields highest efficiency with respect to utilization of material allowables (stressing). In consequence, the resulting line of a design rule, which lies in the lower left area is the design rule, which yields lowest efficiency.

Figure 6 presents the results for the fuselage structure, covered by thermal insulation systems and made from Al 2024 T62 material. The strong dependency of the materials allowables with respect to temperature can easily be extracted from the figure. The thermal term of the design rule always covers the mechanical terms. Further, the ultimate condition of the indirect case is more efficient than the thermal rules of the direct case. Thus, for this structure, its thermal environment and the chosen material, the indirect design rule is most efficient.

Figure 7 presents the results for the fuselage structure made from Al 2024 T81 alloy. In this case, the situation becomes different with respect to the previous example. The thermal design rule for the direct case is not dimensioning at high mechanical loads. At these loads, the direct design rule is even more efficient than the indirect rule, for those areas of the structure, which are dominated by the ultimate design case.

Figure 8 presents results for the Titanium structure, covered by thermal insulation system. Due to the thermal conditions of this structure, only one value for $\sigma_{therm.\text{-}ult.} / \sigma_{therm.\text{-}lim.}$ needs to be considered. Again, this material is not very sensitive to high temperatures, which can be seen in the high efficiency towards thermally dominated design cases. Further, both ultimate rules of the direct design rule are active. As a result, it can be seen,

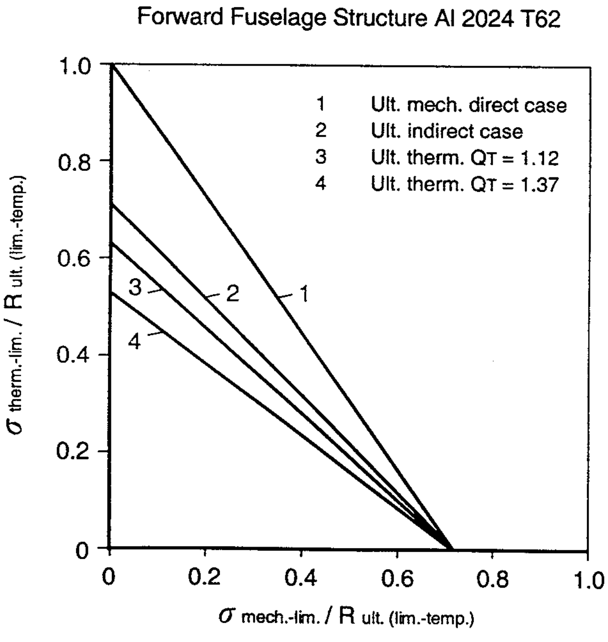


FIGURE 6 – Comparison of design philosophy for forward fuselage structure

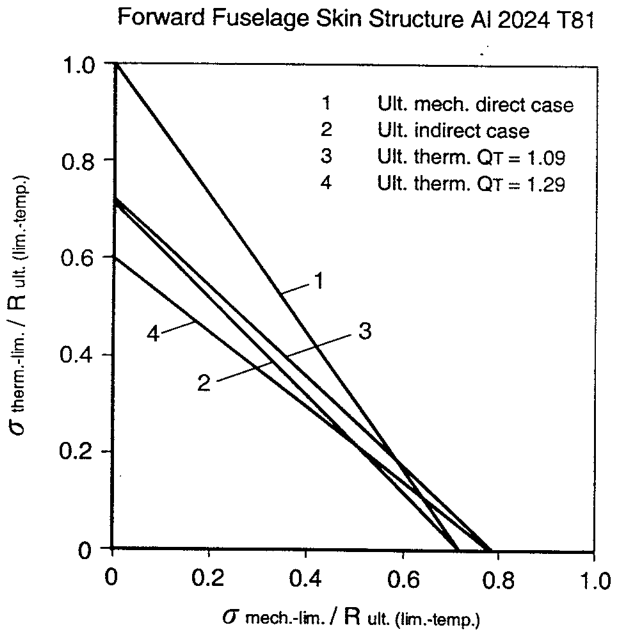


FIGURE 7 – Comparison of design philosophy for forward fuselage structure

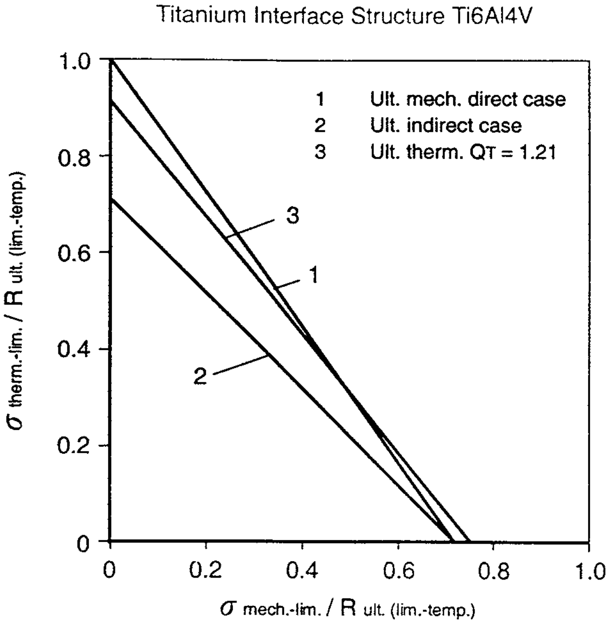


FIGURE 8 – Comparison of design philosophies for Titanium interface structure

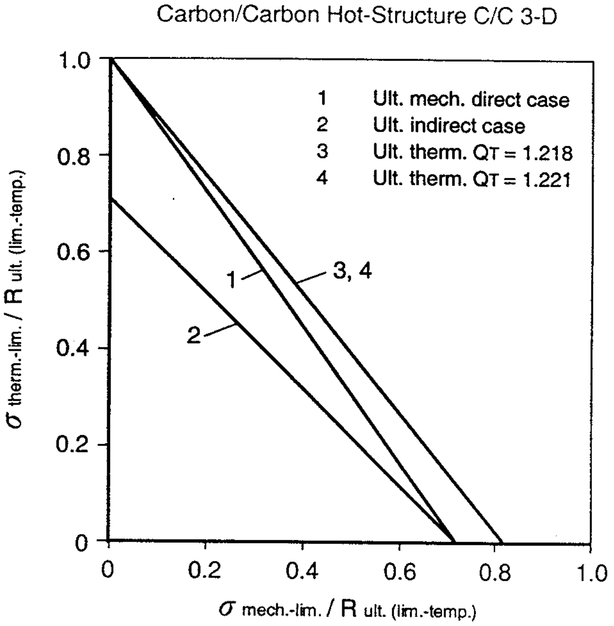


FIGURE 9 – Comparison of design philosophy for nose-cap structure

that the indirect design rule is least efficient with respect to combined mechanical and thermal loading of the Titanium structure. At high thermal loads, the direct ultimate rules are 20% - 30% more efficient and for high mechanical load events just equal the indirect rule.

Results of the fourth example of a C/C hot structure are presented in figure 9. The curves are typical examples for a material which is very insensitive to thermal environment. For the direct ultimate design rules, the mechanical case is least efficient and covers the thermal case over the whole range of possible combinations. Further, the indirect design rule is least efficient over the whole range. In consequence of this structure and the high temperature dominated thermo-mechanical environment, the indirect design rule leads to structures which are less mass efficient.

Specific Design Phenomenon - Thermal Buckling

Since the basis of all structure design examples was to account for and to dimension for the combination of mechanical loads together with thermal loads, the instability phenomenon due to thermal loads building up in the structure have to be considered.

Computations have been carried out for the structures of the previous chapters and in no case the thermal buckling was critical with respect to limit load conditions. However, as further computations on flat panels of a re-entry vehicle wing structure revealed, thermal buckling can occur at loads which are well beyond the design limit loads computed with the described design philosophies. In such case, the structure design has to account for this phenomenon. The consequence is a lower structural efficiency, since the structure is designed for stiffness as the active constraint.

For structures which are sensitive to thermal buckling, further research in this area is to investigate, whether an orthotropic or even anisotropic design can reduce the thermal effects in critical directions and thus, which can reduce the sensivity with respect to thermal buckling of these structures.

Verification Philosophy for Thermally Loaded Structures

The adequate verification of the structures has to be considered from the beginning of the development process and in particular when establishing the design philosophy for the aircraft. As was discussed in previous chapters, the two design philosophies require different approaches for structure verification and for qualification testing.

The indirect method applies the Safety-Factor on the thermal loads. Thus, when it comes to verification by testing, the external conditions have to be adjusted such as to match the specified qualification levels for the thermal loads in all structural elements. This requires an intermediate analysis step for computing the correct test-conditions (heat-flux) to achieve the

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proper thermal loads. Since thermal loads change in every structure element when the external heat fluxes are globally modified by a constant amount, the test-setup may become very complicated.

The direct method, which applied the Safety-Factor on the external thermal conditions, such as the heat-flux, or the inducing performance parameter, is somewhat easier when it comes to verification testing. The specified limit-, acceptance- and qualification conditions can easily be achieved by just modifying the external conditions to the extent required, which renders this design philosophy more efficient with respect to verification testing.

Conclusion

The classical Safety-Factor philosophy for the design of aircraft structures is mainly based on the factorization of the mechanical load environment. This approach requires to be extended by the thermal environment, which high performance supersonic- and hypersonic-aircraft face during high-speed flight. Two possibilities have been discussed for combination of the mechanical environment with the thermal environment. The efficiency of both methods with respect to stressing of the structure has been assessed based on four examples of re-entry vehicle structure. Basis for the discussion was an equal structure "safety", which has been achieved by a proper choice of the Safety-Factor values in both philosophies.

For Aluminium fuselage structures, which are covered by thermal protection systems, for thermal sensitive structures, and thermal sensitive materials in general, application of the thermal Safety-Factor on the induced thermal loads yields best results.

For structures and materials, such as hot structures, which are less sensitive to thermal environment, application of the thermal Safety-Factor on the external heat-fluxes or the performance parameters is the better choice.

Considering the verification of the structure design, application of the thermal Safety-Factor on the external heat-fluxes is easier to be handled during verification testing. A philosophy, which applies the thermal Safety-Factor on the induced thermal loads, requires an intermediate computation for establishing the proper external thermal conditions for testing, which may render the verification of mechanical and thermal loaded structures very complicated and costly.

The design philosophies have been discussed based on structure design for re-entry vehicle. Results may be applied on high performance aircraft structures, if the thermal loading and thermal ageing are comparable. However, further investigations are required for full assessment of the adequacy of the design philosophies for supersonic- and hypersonic-aircraft, since the gain to be achieved with either one of the philosophies depends to a large extent on the trajectories flown and the thermal environment encountered. Further, it depends on the material performance with respect to thermal environment and with respect to thermal ageing.

Reward

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Nomenclature

$\sigma_{lim.}$ → limit load
$\sigma_{ult.}$ → ultimate load
$\sigma_{mech.\text{-}lim.}$ → limit mechanical load
$\sigma_{therm.\text{-}lim.}$ → limit thermal load
$\sigma_{therm.\text{-}ult.}$ → ultimate thermal load
$R_{lim.\ (lim.\text{-}temp.)}$ → limit (yield) material characteristic
$R_{ult.\ (lim.\text{-}temp.)}$ → ultimate material characteristic at limit temperature
$R_{ult.\ (ult.\text{-}temp.)}$ → ultimate material characteristic at ultimate temperature
$\phi_{lim.}$ → limit heat flux
$\phi_{ult.}$ → ultimate heat flux
J → Safety-Factor
$J_{mech.}$ → Safety-Factor for mechanical load
$J_{therm.}$ → Safety-Factor for thermal load or thermal flux
$J_{vel.}$ → Safety-Factor on the design velocity
$V_{lim.}$ → limit or design velocity
$V_{ult.}$ → ultimate or off-design velocity

Remark: In this paper, mechanical and thermal loads are the computed van Mises stresses, to account for the multi-axial load state. For materials with no distinct yield limit, such as composites, the multi-axial stress state is considered within the design criteria for the composite material.

Further to this, 99-percentile probabilities have been considered for the maximum and/or minimum values of the variables: Properties of the structures and of the materials, thermal properties and performance properties (heating, trajectory and atmospheric dispersions).

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