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Alleviation of Thermal Stresses in Aircraft Structures

by

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ALLEVIATION OF THERMAL STRESSES IN AIRCRAFT STRUCTURES

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E. C. Capey

SUMMARY

Methods of alleviating thermal stresses in aircraft structures are discussed under two headings:

(i) Cooling and external insulation.

(ii) Structural design against thermal stresses.

The advantages and disadvantages of each method are noted and the effectiveness is illustrated in some cases by numerical examples. Mention is made of the stresses in honeycomb sandwich and at the boundaries of fuel tanks.

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CONTENTS

1 INTRODUCTION

There exist a variety of methods of alleviating thermal stresses in aircraft subjected to kinetic heating, each method possessing advantages and disadvantages. We shall here summarise and examine each method.

The methods of alleviating thermal stresses may be grouped as follows:

(i) Preventing heating of the structure or allowing heating but evening out the temperature differences.

(ii) Designing to minimise the thermal stresses for a given temperature distribution.

(iii) Choice of an appropriate structural material.

The main methods of preventing heating of the structure are the use, either separately or in combination, of insulation to prevent heat reaching the structure or coolant to absorb the heat which does reach it. An important advantage of these methods is that they eliminate not only the thermal stresses but other undesirable effects of heating, such as temporary or permanent degradation of material properties with temperature, creep, creep buckling and thermal effects on fatigue. The main disadvantages are the weight penalties and the cost of overcoming the considerable manufacturing problems; the weight penalties and some of the manufacturing problems are discussed in Section 2.

Methods of evening out temperature differences include the choice of a type of joint having high thermal conductivity and the use of circulating liquids or high conductivity solid members to transmit heat from one point in the structure to another. The choice of a high conductivity joint has only limited usefulness as often it only has the effect of transferring the site of the temperature drop, leaving the thermal stresses almost as great as before. The use of high conductivity solids has application for conduction of heat over short distances from points of heat concentration, such as stagnation points; for heat conduction over long distance circulating liquids are more efficient. It is unlikely that either would be applied on a large scale as the weight penalty would be severe. Moreover if it were considered worthwhile to install a circulating system to even out temperature differences, it would probably be profitable to carry extra liquid to evaporate, and obtain the advantages derivable from cooling the structure.

Controlled transfer of heat from one part of an aircraft to another, could usefully be applied if air suction were used for boundary layer control. It would be possible, by a suitable choice of path for the hot air to follow after suction into the aircraft, to cause the air to heat webs and other internal structures, thus reducing the temperature differences between the internal structures and the skin. The effect on heating of equipment must, however, be kept in mind.

Design of the structure to minimise the thermal stresses for a given temperature distribution, tends to cause loss of strength and stiffness, a loss which has to be rectified by addition of extra material. However, the weight penalty in the use of corrugated webs, for instance, is likely to be less than that due to using insulation or coolant, so that such methods are preferable if feasible. Two methods in this group considered in more detail are the replacement of straight webs by corrugated or jointed webs, discussed in Section 3.1, and slitting of the leading edge, discussed in Section 3.3. Sections 3.4 and 3.5 consider two types of stresses, viz stresses in honeycomb sandwich and stresses at fuel tank boundaries, which are difficult to alleviate by structural design, and seem to require a method of alleviation which reduces the temperature differences.

Alleviation of thermal stresses by choice of structural material is possible only to a limited extent. If one material is clearly the most suitable on mechanical grounds and is able to withstand the temperature to which it is to be subjected, one would be reluctant to abandon it because of thermal stresses. If, on the other hand, two materials were otherwise comparable, a difference in thermal properties causing the thermal stresses in one to be more severe than those in the other might be of sufficient significance to determine the choice of material. The properties on which the thermal stresses depend are the coefficient of thermal expansion, Young's modulus, specific heat and thermal conductivity. We shall examine briefly the significance of each.

For a given temperature distribution the thermal stresses are proportional to the product of the coefficient of thermal expansion and of Young's modulus. A low value of the former is clearly desirable. On the other hand a high value of Young's modulus is desirable on mechanical grounds, and generally remains so even when thermal stresses are present. For example if thermal buckling is liable to occur, the thermal stresses tending to produce buckling are proportional to Young's modulus, but so is the critical stress at which buckling occurs, so that the critical temperature difference is independent of Young's modulus. If mechanical and thermal stresses are combined the critical temperature difference rises with Young's modulus.

A high specific heat is advantageous in the skin to slow down its rate of heating, but disadvantageous in an internal structure, as it makes the temperature of the internal structure lag behind that of the skin. If skin and internal structure are of the same material, a high value of specific heat may or may not be desirable, as one or other of these considerations will be dominant.

A high thermal conductivity is always desirable in order to reduce the extent to which the temperature of the internal structure lags behind that of the skin. The nature of this effect may best be seen by considering an example, that of a web between two heated skins, the depth of the web being D, its thermal conductivity k, its heat capacity per unit volume ρc, and its diffusivity, κ, defined as $k/\rho c$. It can be shown that the temperature of the middle of the web lags behind that of the skin by a time $D^2/8\kappa$. If the skin is heated from one temperature level to another, in a period of time less than $D^2/8\kappa$, almost the full applied temperature differences occurs between the skin and the middle of the web whatever the diffusivity of the web, but if the skin is heated slowly the maximum temperature difference between the skin and the middle of the web is proportional to the time lag, so is inversely proportional to the diffusivity.

2 COOLANT AND EXTERNAL INSULATION

2.1 Coolant

The use of coolant can in principle eliminate thermal stresses. In this respect it is superior to those methods based on allowing temperature differences to occur and designing the structure to minimise the resulting thermal stresses.

The choice of coolant lies between the fuel and liquid carried specifically as a coolant. If the fuel is capable of providing an adequate heat sink for structural cooling, in addition to satisfying any demands that may be made on it by the engine, this solution is ideal; as the fuel has to be carried anyway, the only weight penalty is that of the piping and additional pumping equipment required to transport the fuel round the structure. However, if the heat capacity of the fuel is not adequate an additional liquid coolant must be carried. The basic property required of such a liquid is a high heat capacity between the temperature of the aircraft on the ground and the maximum allowable temperature of the structure. A liquid which vaporises within this range of temperature possesses the great advantage that its latent heat may be utilised. Water is a particularly good coolant, as it is readily available, and possesses very high latent heat and specific heat. The specific heat in the liquid state is 1 CHU/(lb°C) and the latent heat is 540 CHU/lb at 100°C. The latent heat is greater at lower temperatures, but no additional cooling capacity is gained by evaporation at a lower temperature as the increase in latent heat is balanced by a change of specific heat from that of the liquid state to that of the vapour state.

The utilisation of the latent heat of vaporisation presents some problems, since it is necessary to vaporise the liquid and dispose of the vapour without losing any of it in a liquid form before its latent heat has been utilised. Two solutions to these problems appear satisfactory:

(i) Transpiration cooling, in which the liquid is stored within the structure, then evaporates on heating through pores in the structure. This method possesses the advantage (examined by Eckert[1]) that, apart from cooling the structure, the vapour cools the boundary layer and reduces the heat input to the structure. The use of transpiration cooling introduces manufacturing difficulties, in that the whole surface of the aircraft has to be porous - difficulties which are aggravated if insulation is used in combination with cooling. Transpiration cooling may increase the drag by bringing forward the transition from laminar to turbulent flow.

(ii) Use of a second liquid for circulation and a heat exchanger. The circulating liquid, whose boiling point must be higher than that of the heat sink liquid, is pumped round the structure and back to the heat exchanger, where the heat it has absorbed is transferred to the evaporating heat sink liquid. On leaving the heat exchanger it is ready to be circulated again. Bell Aerosystems have applied this system succesfully[2] using water as the heat sink liquid and aqueous glycol as the circulating liquid.

Disadvantages of cooling by circulation are that a considerable quantity of equipment is required, including piping, pumps, a heat exchanger and control equipment, and there is a severe weight penalty due to this and due to the large quantity of coolant required. The pipes could be used as load bearing members, but are not likely to represent an economical use of material from a purely structural point of view. Comparable weight penalties apply if transpiration cooling is used instead of cooling by circulation of liquid.

The weight of circulating liquid, piping and other equipment required can be calculated only for a specific design layout, but the weight of coolant evaporated depends only on the quantity of heat entering the structure, which can be calculated from the aerodynamic conditions to which the aircraft is subjected.

Calculations on these lines have been performed by Wolfe[3] and the weights obtained compared with the weights of a typical insulation required to protect an aircraft subjected to the same conditions and also with the required weights of coolant and insulation in combination. These results are discussed in Section 2.3.

2.2 External insulation

The external insulation of aircraft structures presents special problems, as any material forming the outer surface of the aircraft must possess resistance to rain erosion and to atmospheric corrosion and erosion at elevated temperatures, and must be capable of a reliable bonding to the structure. An external insulation must, moreover, retain these properties after repeated subjection to stresses caused by the temperature differences across it and by straining in sympathy with the structure. Thus, whereas internal insulation may be selected solely on its thermal properties, that is conductivity, density and ability to survive the applied temperatures, external insulation also requires acceptable mechanical and bonding properties.

One solution to these problems is to cover the insulation with metallic shields. Such shields must be able to withstand exposure to the atmosphere at the applied temperature, but if carefully designed they need not possess high mechanical strength at these temperatures, their function being reduced to that of holding the insulation in position. In a design based on this principle, adjacent shields are made to overlap in such a manner that they can expand on heating without inducing thermal stresses. The gaps between shields also serve to allow air to penetrate under pressure, so that the internal skin carries the pressure loads. A disadvantage of this system is that the moisture tends to penetrate the gaps between shields and to soak the insulation. To prevent this the insulation must either be enclosed in waterproof bags or else be chemically waterproofed; chemical waterproofing is not yet practical for insulation subject to very high temperatures. The insulation, being protected, may be chosen purely for its thermal properties. Fibrous or foamed insulations appear satisfactory, as they have low conductivity and density and are subject to little thermal stress on heating. The metallic shield has to be connected to the structure in such a manner as to be free to expand on heating, but must be rigid against outwards movement. Connections of this type can be achieved in several ways, for example by hinged joints. Some heat is bound to be transferred to the structure through the joints, but the quantity need not be excessive. Bell Aerosystems have built shields of honeycomb material[2], which seems to be capable of withstanding severe environmental conditions, and whose weight is not prohibitively high.

The alternative to shielding the insulation is to choose an insulation that is able to withstand the air and rain erosion and is capable of a reliable bond to the structure. If the aircraft is subjected to severe heating a ceramic material has attractive features, in particular certain ceramics can withstand the erosion even at elevated temperatures. Thermal stresses are, however, a serious problem. The thermal conductivity of ceramic materials is much higher than that of fibrous insulation, and the density is high, so that the provision of an adequate layer of ceramic may present a weight penalty. If the heating is less severe, durestos, or some similar material, appears more satisfactory, as its thermal properties are better than those of ceramics, though still inferior to those of fibrous materials, and it has good resistance to thermal stresses.

An insulated structure recently developed by the Aeronca Manufacturing Corp[2,4,5] is shown in Fig.1. This structure is composed of an outer layer of foamed ceramic to withstand the erosion and an inner layer of fibrous insulation fixed on to a sandwich structure. The foamed ceramic is held in place by a honeycomb of steel foil. The cutting of the ceramic into segments by the honeycomb reduces the thermal stresses it suffers on heating, but on the other hand, even though the steel honeycomb is very thin its contribution to the conductance is considerable.

2.3 Coolant and external insulation in combination

If cooling and insulation are used in combination the total weight of thermal protection required may be less than that required using either on its own. The presence of a layer of insulation reduces the quantity of heat entering the structure and consequently the quantity of coolant required, and also the weight of piping and other equipment. On the other hand the presence of coolant to absorb heat penetrating the insulation reduces the demands on the insulation so that a thinner layer may be used. There exists, in general, an optimum combination of coolant and insulation which provides the required thermal protection to a structure for a minimum weight penalty. General methods of calculating optimum configurations are presented in Ref.6.

McCue[7] has calculated the optimum configuration for thermal protection of an aircraft flying at constant speed over a range of either 2500 miles or 5500 miles, its structure being built of an aluminium alloy whose maximum allowed temperature is 150°C. The aircraft is protected by combined cooling and insulation, its cooling system being based on the evaporation of water, and the insulation being a low density durestos type material of density $31{\cdot}2$ lb/ft^3 and thermal conductivity $4{\cdot}37 \times 10^{-5}$ CHU/(ft sec°C). The weights of combined coolant and insulation calculated by McCue are compared by Wolfe[3] with the weights of coolant alone or insulation alone required to protect an aircraft subjected to the same flight conditions using the same materials for thermal protection. Some of his results are presented in Fig.2, which shows the weights of coolant alone, of insulation alone and of combined coolant and insulation required by an aircraft flying either 2500 miles or 5500 miles at a Mach number of 4 at an equivalent air speed of either 200, 300, 400 or 500 knots. These values of E.A.S. cover the practical range, as an E.A.S. of 200 knots gives barely sufficient lift and an E.A.S. of 500 knots severely loads the aircraft. As the Mach number increases above a value of 4 the quantity of heat received by the aircraft does not change much, nor do the required weights of coolant, insulation or combined coolant and insulation. This result appears surprising, as the adiabatic wall temperature increases rapidly with Mach number, but there are two effects compensating for this - the decrease of the flight time with increase of Mach number, and the reduction of air density, and consequently of heat transfer coefficient, as the Mach number increases at constant E.A.S. Fig.2 shows that at low E.A.S. coolant on its own protects the aircraft as economically as coolant and insulation in combination, but at high E.A.S. combined coolant and insulation are necessary, as either on its own is much heavier.

The most significant conclusion from this work is that an aircraft may be protected from severe kinetic heating under most practical conditions with a total thermal protection weight of the order of 2-4 lb per square foot of surface protected. All of this work concerns insulating materials fixed unprotected on the surface of the aircraft. If, instead, a low density, low conductivity insulating material is used protected from the environment by a metal shield, the weight of insulation required is reduced, but the metal shield has an appreciable weight itself. Present indications are that such a design is lighter than one using hard unshielded insulation, giving weight penalties lower than those calculated by Wolfe.

3 STRUCTURAL DESIGN AGAINST THERMAL STRESSES

We shall consider here the design of certain structural components to alleviate particular types of thermal stress.

3.1 Corrugated and jointed webs

When an aircraft is subjected to kinetic heating the skin heats up more rapidly than the webs, causing compressive stress in the skin and tensile stress in the webs. As there is usually more material in the skin than in the webs, the tensile stress in the webs is usually the greater, but the compressive stress in the skin may be serious, due to its tendency to cause buckling. Both stresses may be considerably reduced if straight webs are replaced by corrugated webs or webs with expansion joints, which have less tensile rigidity because they are able to elongate by bending. Some analysis of the behaviour of webs with expansion joints is presented here. The flexibility and thermal stresses in corrugated webs have been examined by Williams[8].

Fig.3, shows some corrugated webs and webs with expansion joints and the points at which they are connected to the skin. Corrugated and jointed webs have greater flexibility than straight webs even when attached continuously to the skin, though to attain its maximum flexibility a corrugated web should be attached at only one point per corrugation and a jointed web at only one point between successive joints. The 'point of attachment' may extend a short distance without appreciably reducing the flexibility of the web, and may need to do so to reduce the stress concentration at the attachment. Fig.3 gives formulae for the flexibility of corrugated webs and webs with expansion joints and for the maximum stress in the web due to a unit elongation of the skin, both of these properties being expressed relative to those of a straight web. The flexibility is a measure of the extent to which the skin stresses produced by the web have been relieved. Values of the flexibilities and maximum stresses have been calculated, and recorded in Fig.3, for two illustrative examples - that of a corrugated web of thickness 0·1" with corrugation of height 2" and pitch 20", and that of a web of the same thickness, with an expansion joint of length 2" every 20". It is found that very high flexibilities are attained in all cases, but appreciable stresses remain, particularly in the web with expansion joints.

For various reasons, including that of stress concentrations at the joints, it may be desirable to attach the web continuously to the skin even though this increases the rigidity of the web. The following simplified analysis estimates the rigidity and stresses in a web with expansion joints, with dimensions as shown in Fig.4, attached continuously to a thick skin. Some of the conclusions from this analysis also apply to corrugated webs. To simplify the analysis the joints are assumed to possess no rigidity and forces in the y-direction (depth-wise) are ignored, a condition represented mathematically by equating the direct stress σy to zero and eliminating the equilibrium equation and boundary conditions for forces in the y-direction. With these simplifications the problem reduces to finding a solution of Laplace's equation, which was obtained by a finite difference technique.

Despite the crudity of the assumptions the accuracy is adequate to illustrate the basic trends. In Fig.4 the rigidity of the web is plotted against the ratio ℓ/D, where D is the depth of the web and ℓ the distance between joints. It is shown that the rigidity is halved if the distance between expansion joints is about 1·5 times the depth of the web.

The stresses in a web with expansion joints continuously connected to the skin depend on the temperature distribution through the web. If the web is of uniform temperature, then there is no reduction in the maximum stress, which occurs at the junction with the skin. In practice the temperature distribution is often approximately parabolic, in which case the maximum stress occurs at the middle of the web, and is reduced by the presence of expansion joints. Results of calculations for this case are also presented in Fig.4. It is shown that the stress is halved if the distance between expansion joints is about 1·3 times the web depth.

3.2 Leading edge stresses

When an aircraft is subjected to kinetic heating, there is a chord-wise variation in skin temperature, because the adiabatic wall temperature and the heat transfer coefficient both reduce with increasing distance from the leading edge. The skin temperature distribution may be affected by a transition from laminar to turbulent flow, but the transition point is generally so mobile that its influence on the temperature distribution is not noticeable. A typical chord-wise temperature distribution might approximate to the form

$$\theta = A + B \exp(-y/y_0) \qquad (1)$$

where y is the distance from the leading edge and A,B and y_0 are constants. Fig.5(a) shows the distribution of thermal expansion for a wing composed of a single material and with the temperature distribution of equation (1). The wing bends on heating, in the plane of the wing, producing a strain distribution which is approximately linear across the chord for a wing of finite span, and leaving residual stresses which are proportional to the difference between the thermal expansion and the strain. The constants in the strain distribution can be calculated on the assumption that the total force and moment across the chord due to thermal stresses must be zero. Fig.5(a) shows how the stress varies across the chord for a wing of uniform cross-section made of a single material, and demonstrates that the most severe stresses occur at the leading edge. As these stresses are compressive they may produce buckling. Moreover the distribution of stresses, tensile in the middle, compressive at leading and trailing edges, reduces the overall flexural and torsional stiffness of the wing.

Wings have been proposed, made of two materials, one with good low temperature properties and another with good high temperature properties. The effect on the thermal stresses of using two materials depends on the relative values of the coefficients of expansion of the two materials. If the high temperature material has a higher coefficient of expansion, the compressive stresses in it will be severe, the large expansion it would have if free to expand on heating being prevented by the low temperature material in the rest of the wing. It might be thought, on the other hand, that if the high temperature material had a lower coefficient of expansion than the low temperature material, the thermal stresses would be reduced. To test this proposition calculations have been performed for a case in which the coefficient of expansion of the material near the leading edge is half that of the rest of the wing. The results are presented in Fig.5(b). It is shown that the stresses are about as severe as those in a wing composed entirely of the material with the higher coefficient of expansion, but the distribution of stresses is different.

3.3 Leading edge slits

Slits in the leading edge allow the leading edge to expand independently of the rest of the wing, thus reducing the thermal stresses in the rest of the wing. The slits have two disadvantages; they reduce the stiffness and strength of the unheated wing, and unless carefully designed they may produce turbulence and diversion of the airstream, which may produce localised heating and additional thermal stresses. In the X.15 simple slits were cut in the leading edge, which produced diversion of the airstream and leading edge buckling[9]. These faults were remedied by using telescopic joints in place of simple slits. Fig.6 shows the original and modified leading edges after subjection to heating. The loss of stiffness and strength can be assessed by assuming that the material in front of the ends of the slits makes no contribution.

The effectiveness of leading edge slits depends on the spacing and on the skin thickness, the presence of webs or fillets and the temperature distribution of the particular configuration. To illustrate the nature of the problem a simple case has been analysed, in which the wing is represented as a flat plate of uniform thickness subjected to a temperature distribution as given by equation (1). Part of the wing is shown in Fig.7. The span and chord are both taken to be effectively infinite. It is required to find how the maximum stress in the wing varies with the distance between slits, assuming that the slits extend far enough to cover the region where the temperature varies appreciably. As this problem is only illustrative, considerable simplifications in the mathematics are permissible, and therefore forces in the y-direction have been ignored, as they were in the problem of the continuously connected web. The problem is again reduced to that of finding a solution of Laplace's equation, which was obtained by a finite difference technique. Fig.7 shows how the maximum stress in the leading edge, which always occurs midway between slits, varies with the distance between slits. The presence of leading edge slits halves the maximum thermal stress if the distance between slits is $2\frac{1}{2}$ times the constant y_0 in the exponential in the temperature distribution, and reduces the thermal stresses to a quarter if the distance between slits is 0·9 times this constant.

3.4 Stresses in honeycomb sandwich

If honeycomb sandwich is used in an aircraft subjected to kinetic heating, the temperature of the outer face of the sandwich rises faster than that of the inner face. If the sandwich is restrained against bending this produces compressive stress in the outer face and tensile stress in the inner face. To illustrate the factors on which the magnitude of these stresses depends a simplified version of the problem is considered, in which a two-dimensional sandwich, as shown in Fig.8, with faces of thickness t_1 joined by honeycomb foil at a pitch ℓ of depth D and thickness t_2, is heated at a constant rate $\dot{\theta}$ on one face and insulated on the other face. Assuming that heat is transferred through the honeycomb only by conduction and that there is no joint resistance between the faces and the honeycomb and neglecting the thermal resistance of the faces, it can be shown that the temperature difference between the faces rises to a value

$$\Delta\theta = \left(\frac{2\ell t_1 + Dt_2}{Dt_2}\right)\frac{\dot{\theta}D^2}{2\kappa} \tag{2}$$

giving rise to stresses

$$\sigma = \pm\left(\frac{2\ell t_1 + Dt_2}{Dt_2}\right)\frac{E\alpha}{2\kappa}\,\dot{\theta}\,D^2 \tag{3}$$

in the faces of the sandwich from which we see that the magnitude of the stresses depends on the material, the rate of heating, the depth of the honeycomb and varies inversely as $Dt_2/(2\ell t_1 + Dt_2)$ which is the proportion of the material in the honeycomb. For a three-dimensional honeycomb sandwich the solution is identical, except that the expression representing the proportion of the material in the honeycomb differs.

Calculations have been performed for a sandwich of depth 1 inch, composed either of aluminium alloy or of stainless steel, heated at a rate of 1°C per second. The stress is plotted in Fig.8 against the proportion of the material in the honeycomb. It may be seen that the stress in an aluminium honeycomb sandwich is much less than that in a steel sandwich, for which a reduction of the quantity of material in the honeycomb to a minimum produces severe stresses.

Possible methods of alleviating the thermal stresses in honeycomb sandwich, assuming one does not intend to insulate or cool the whole structure, are to decrease the depth of the sandwich, to increase the proportion of the material in the honeycomb, or to choose a material with suitable thermal properties. The use of expansion joints is unsatisfactory, as expansion joints in either face of the sandwich would remove the stiffness of that face and hence its usefulness.

3.5 Stresses at fuel tank boundaries

In a heated wing with integral fuel tanks, temperature differences occur between the skin covering fuel tanks and that not covering fuel tanks, the former being cooled by the fuel, as shown in Fig.9(a). These temperature differences cause stresses near the fuel tank boundaries - compressive in the skin not covering fuel tanks and tensile in that covering the tanks. If the fuel is held in bags, the temperature gradient at the boundary of the tanks is reduced, but the maximum stress only marginally affected. The use of slits or expansion joints to alleviate these stresses is not practical, as this would cause serious loss of strength and stiffness in the structure and produce adverse aerodynamic and aeroelastic effects.

For a fuel tank in the fuselage appreciable bending stresses may be produced in the fuselage shell near the tank bulkhead, because it is there that the radial expansion that occurs outside the tank has to be accommodated, Changes in skin thickness in this region aggravate the situation.

If the fuel tank is insulated internally (as it might be to prevent overheating of the fuel) then the tensile and compressive stresses in the skin are reduced, but additional stresses are produced by the temperature difference across the insulation shown in Fig.9(b) - stresses which are compressive in the outer skin covering the fuel tanks and tensile in the inner fuel tank walls. These stresses may be relieved by expansion joints in the fuel tank walls or by making the insulation and the end fixings of the tank sufficiently flexible. If the tank is in the fuselage additional stresses are caused by radial expansion of the hot outer skin.

If the aircraft is insulated externally the skin temperature becomes uniform. The only stresses present are those due to expansion of the insulation, the magnitude of which depends on the rigidity of the insulation.

4 CONCLUDING REMARKS

It is shown that there are two basic methods of alleviating thermal stresses in aircraft subjected to kinetic heating: (i) to prevent heating of the structure by use of coolant, insulation, or coolant and insulation in combination, and (ii) to permit heating but design structural components to reduce the stresses. Each method possesses distinct merits and demerits, which make one or the other the more suitable for particular aircraft structures.

Component design includes the use of corrugated webs, expansion joints and leading edge slits. These methods cause loss of stiffness and strength in the structures, but possess the merit of considerably reducing some of the thermal stresses for a small weight penalty. Moreover their engineering problems are fairly well understood.

The use of corrugated webs etc can be adopted for mild heating, but if the heating is severe, insulation and/or cooling must perforce be accepted. There remains an intermediate regime where the use of insulation and cooling may well be competitive with structural design methods. It should be emphasized, however, that the engineering problems in the use of insulation and cooling are formidable.

SYMBOLS

A, B	constants in equation (1)
c	specific heat
D	depth of web or sandwich
E	Young's modulus
h	depth of corrugations; length of expansion joints
k	thermal conductivity
ℓ	distance between expansion joints or slits; honeycomb cell width
t	thickness of web
t_1	thickness of sandwich face
t_2	thickness of honeycomb foil
U, V	displacements
x, y	rectangular co-ordinates
α	coefficient of expansion
θ	temperature
$\dot{\theta}$	rate of rise of temperature
κ	diffusivity
ν	Poisson's ratio
ρ	density
σ_x, σ_y	direct stresses
τ_{xy}	shear stress

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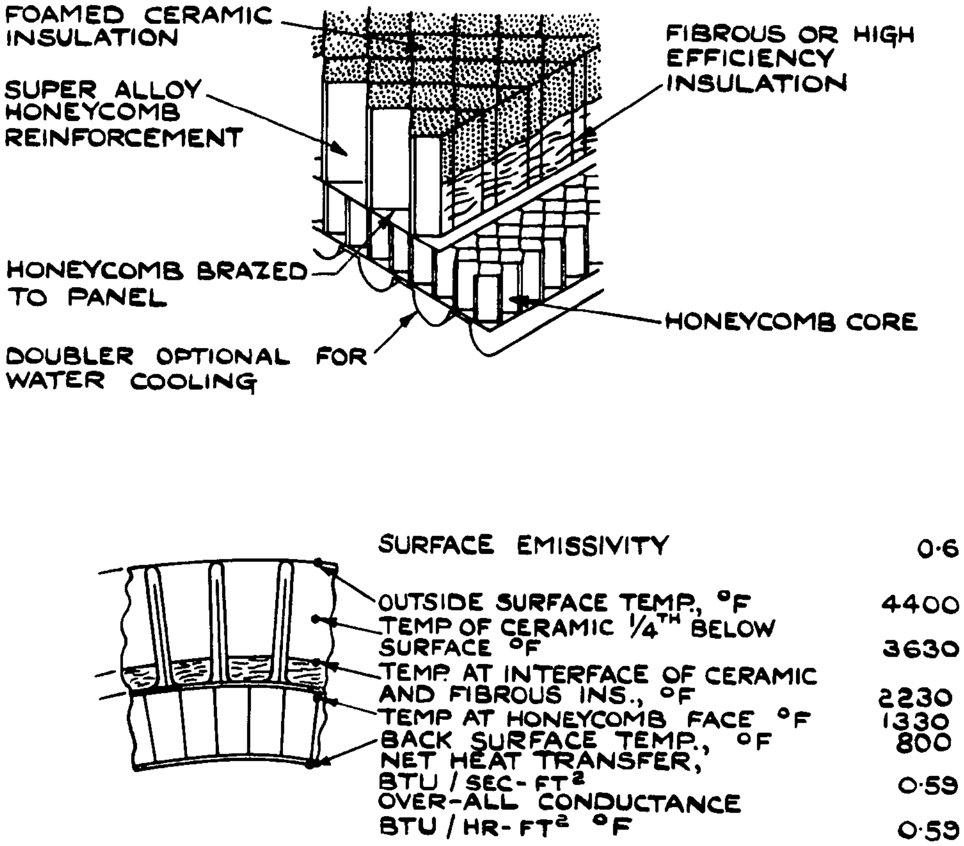


FIG. 1 INSULATED STRUCTURE DESIGNED BY AERONCA MANUFACTURING CORP

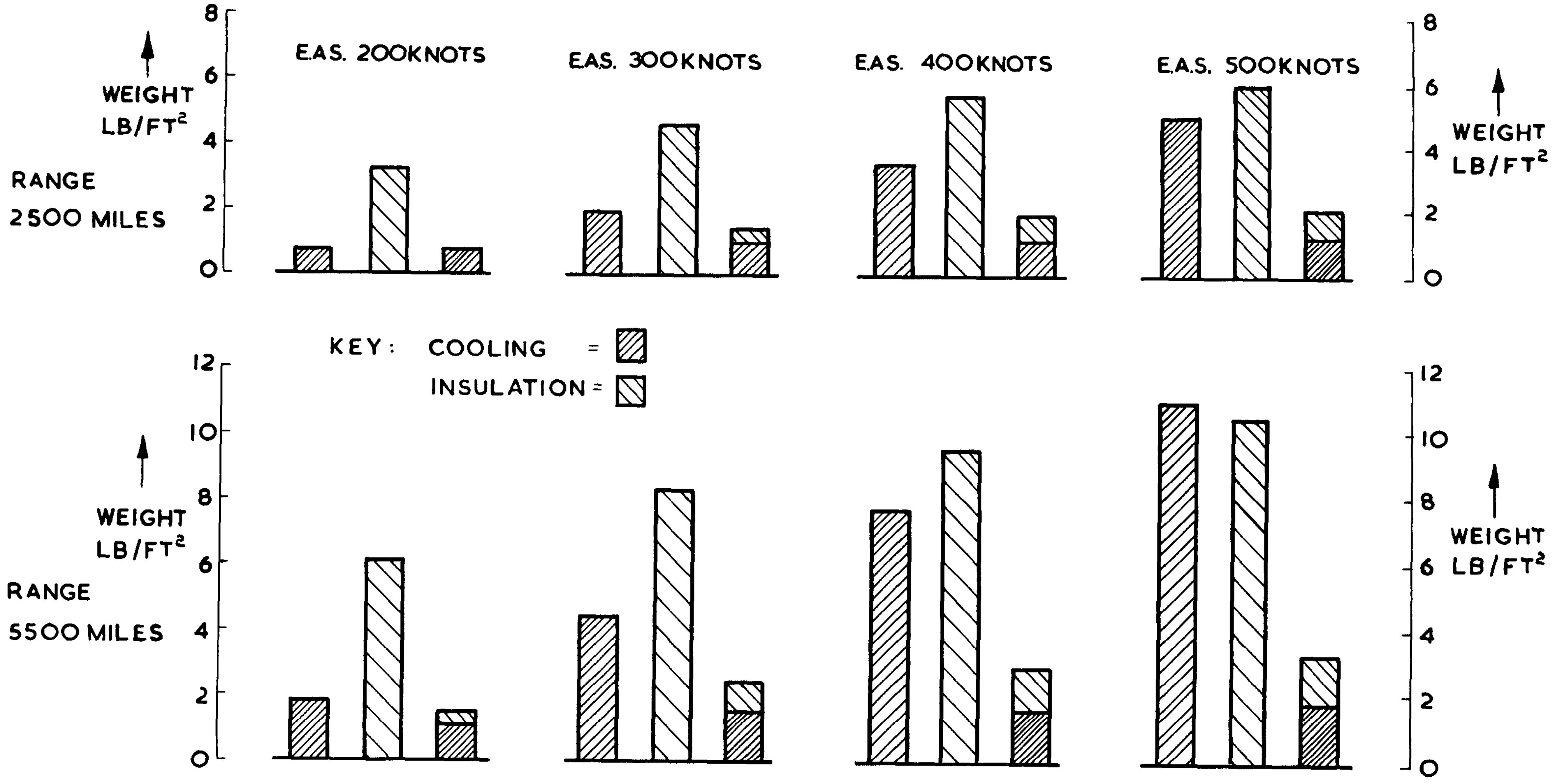
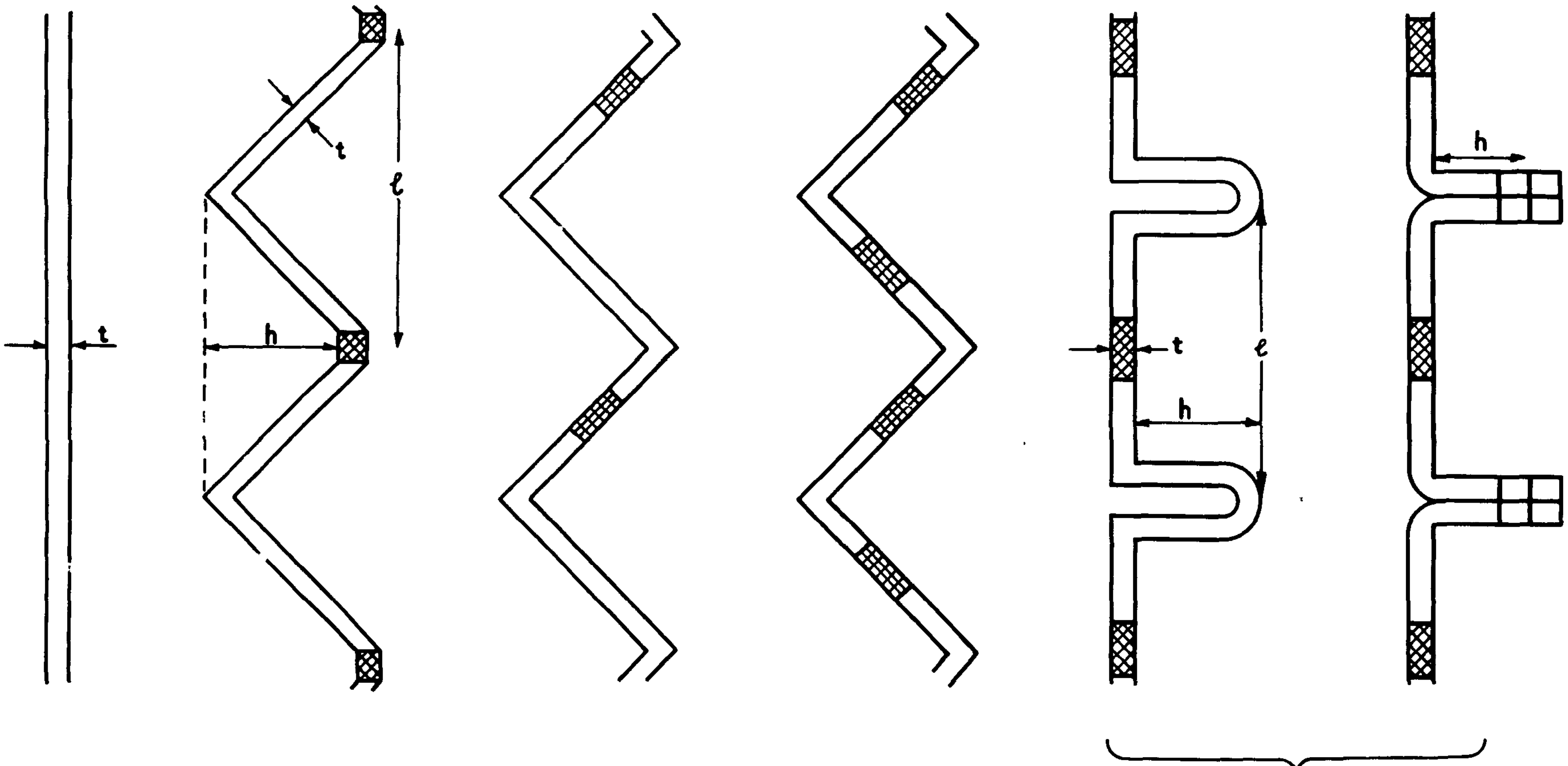


FIG.2 COMPARISON OF WEIGHTS OF COOLANT, INSULATION & COMBINED COOLANT & INSULATION FOR A MACH NUMBER OF 4



FLEXIBILITY	1	$(1-\nu^2)\frac{h^2}{t^2}$ (360)	$\frac{7}{16}(1-\nu^2)\frac{h^2}{t^2}$ (158)	$\frac{1-\nu^2}{4}\,\frac{h^2}{t^2}$ (90)	$8\,(1-\nu^2)\frac{h^3}{t^2\ell}$ (288)
MAXIMUM STRESS	1	$\frac{3t}{h}$ (0·15)	$\frac{36t}{7h}$ (0·26)	$\frac{6t}{h}$ (0·3)	$\frac{3\ell t}{4h^2}$ (0·38)

FIGURES IN PARENTHESES REFER TO CASE $t = 0{\cdot}1''$, $h = 2''$, $\ell = 20''$ AND $\nu^2 = 0{\cdot}1$

FIG. 3 FLEXIBILITIES AND THERMAL STRESSES IN CORRUGATED WEBS

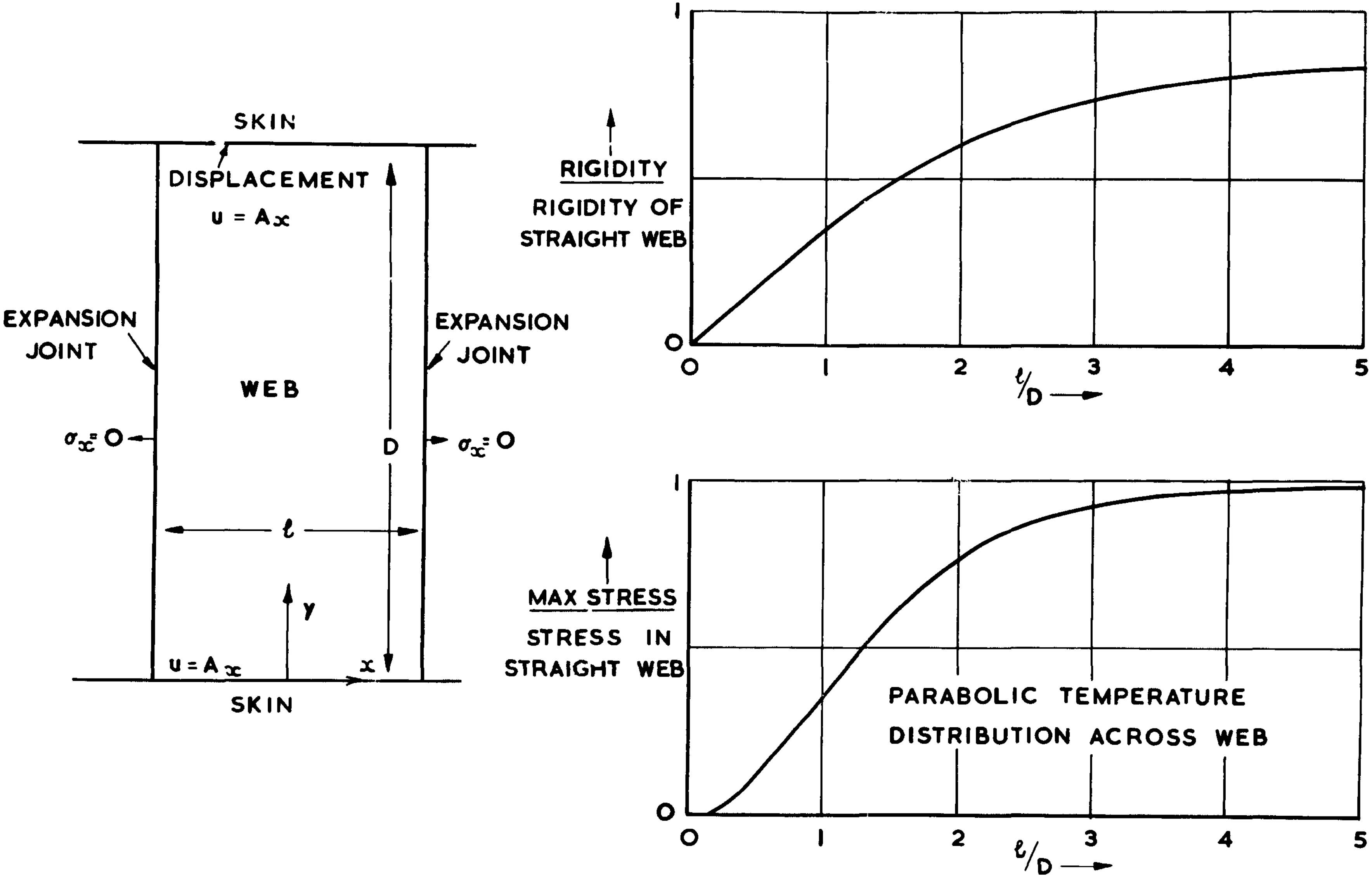
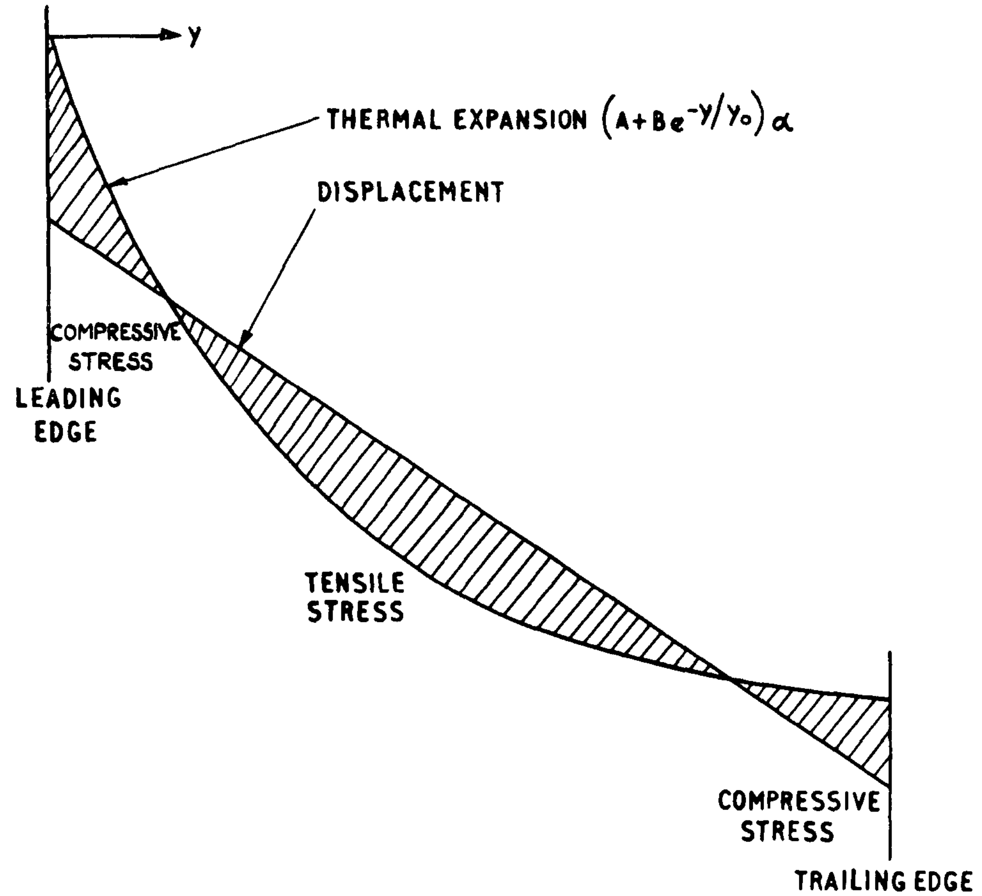
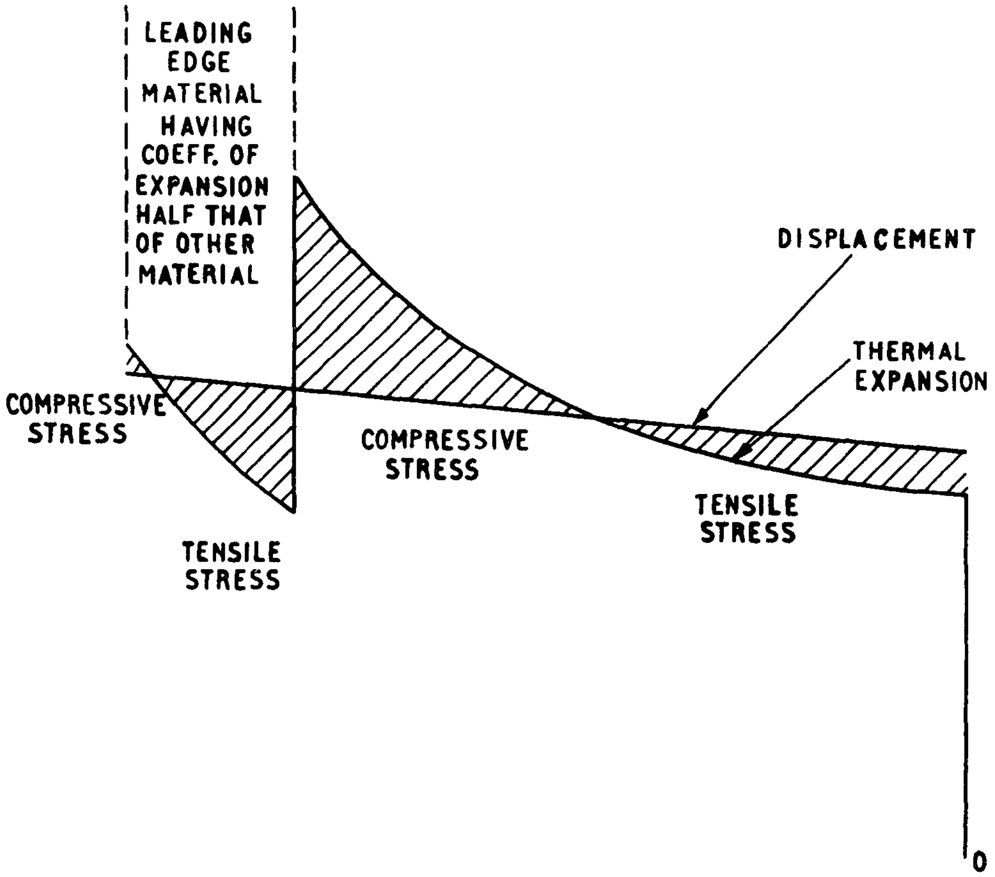


FIG.4 RIGIDITY AND MAXIMUM STRESS IN CONTINUOUSLY CONNECTED WEB WITH EXPANSION JOINTS



(a) THERMAL STRESSES IN A WING COMPOSED OF ONE MATERIAL



(b) THERMAL STRESSES IN A WING COMPOSED OF TWO MATERIALS

FIG. 5 (a & b) THERMAL STRESSES IN A HEATED WING

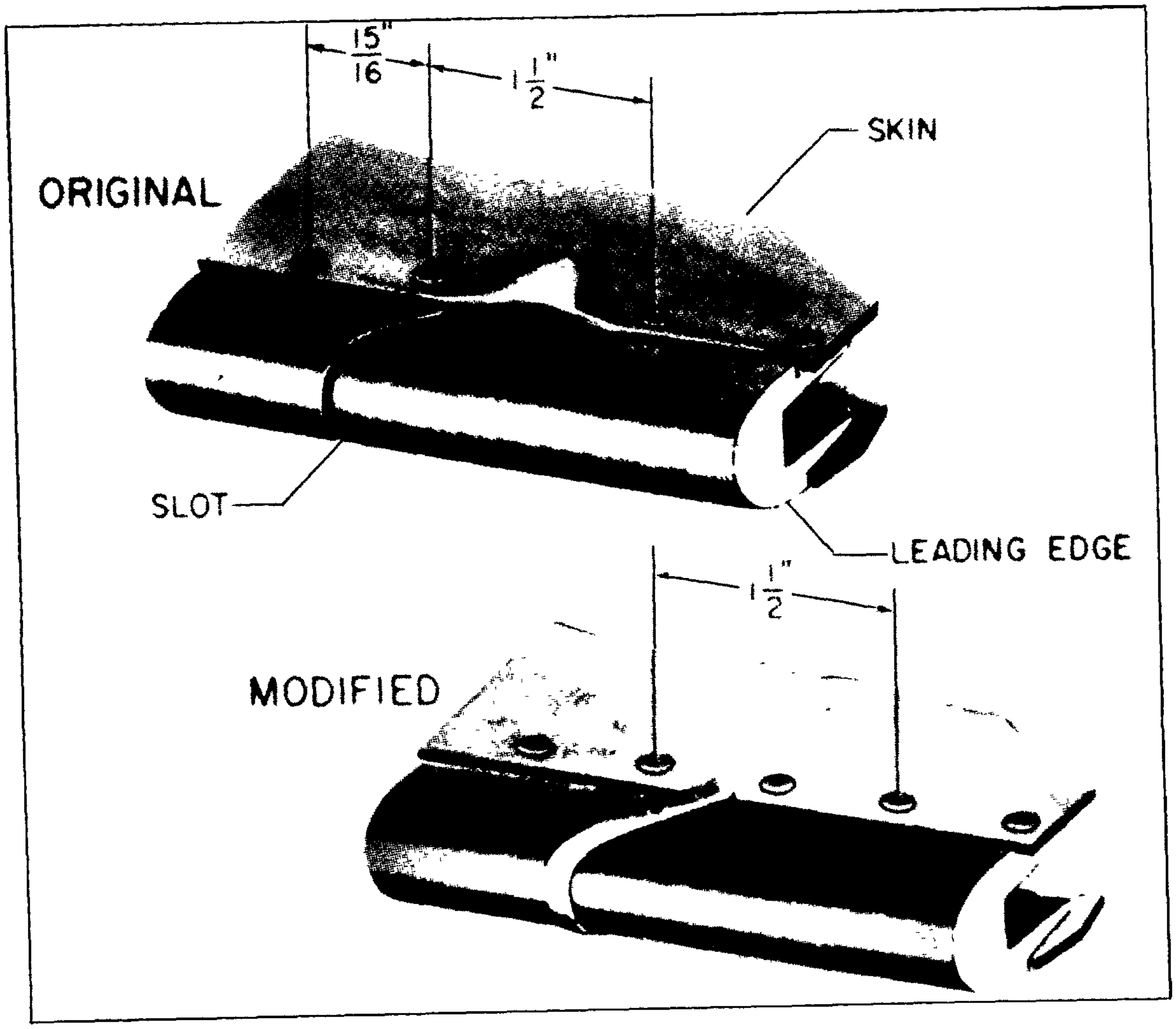


Fig.6 Leading edge buckle in the x.15 (Reprinted from Ref. 9)

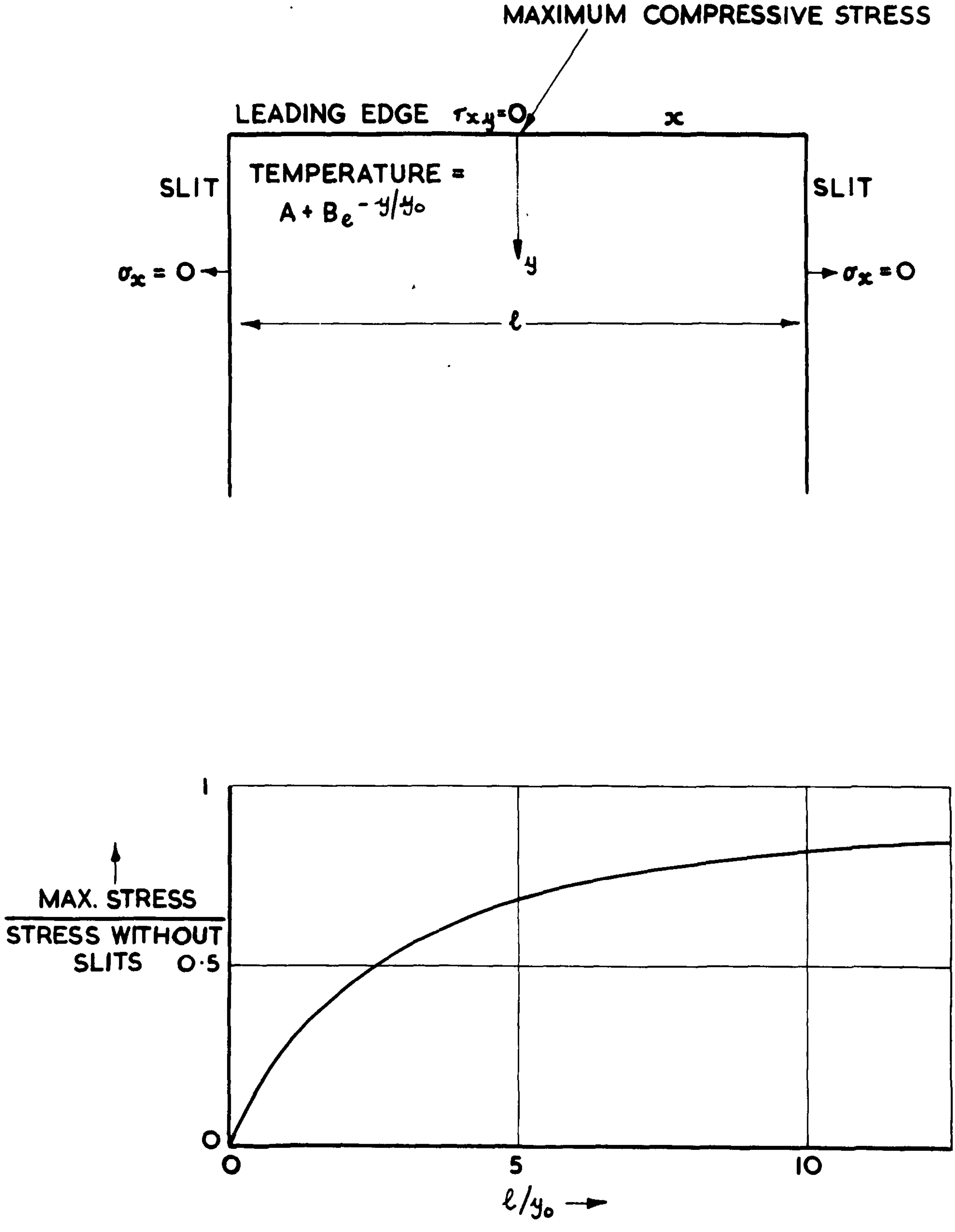


FIG. 7
MAXIMUM STRESSES BETWEEN LEADING EDGE SLITS

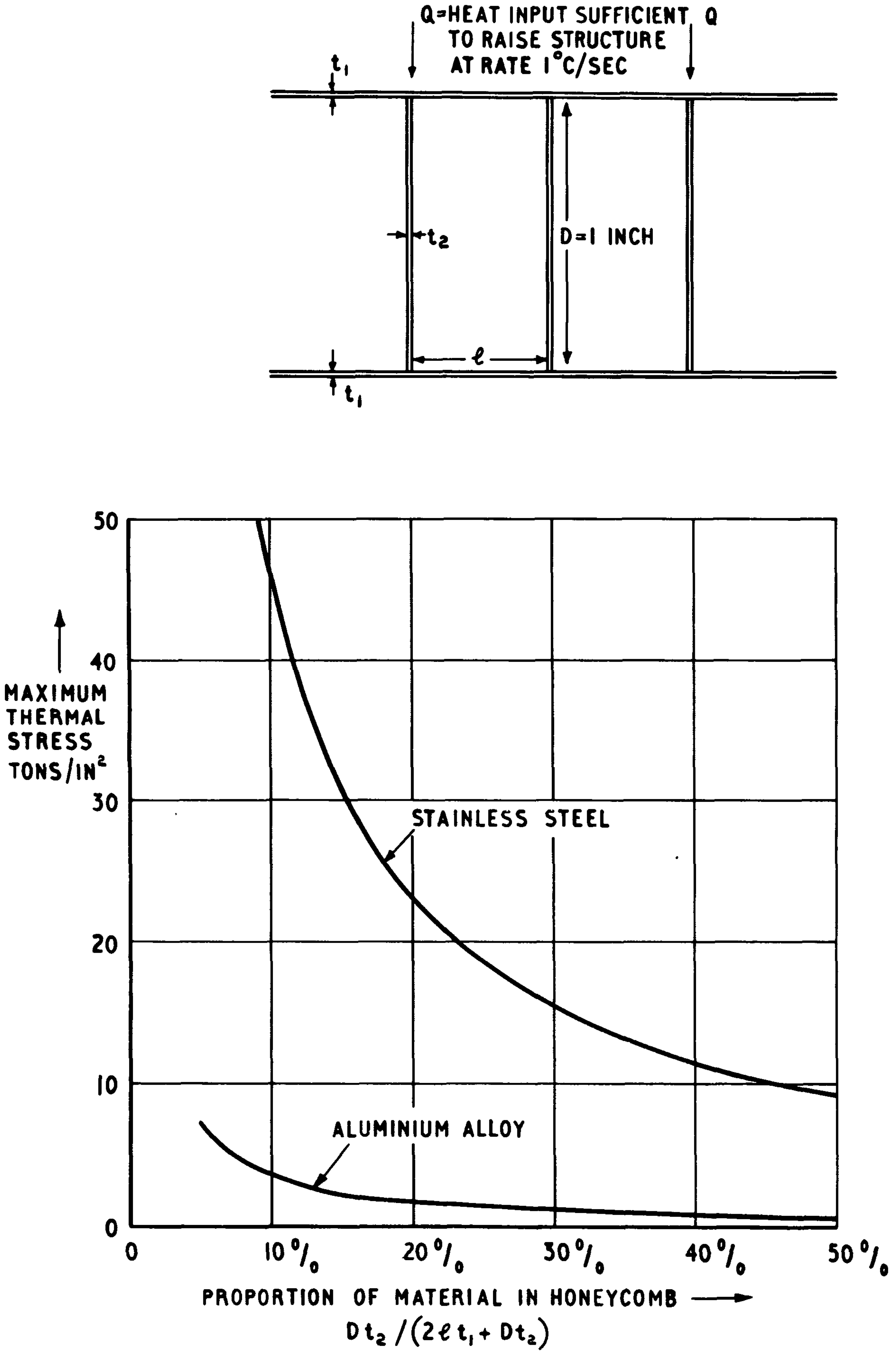
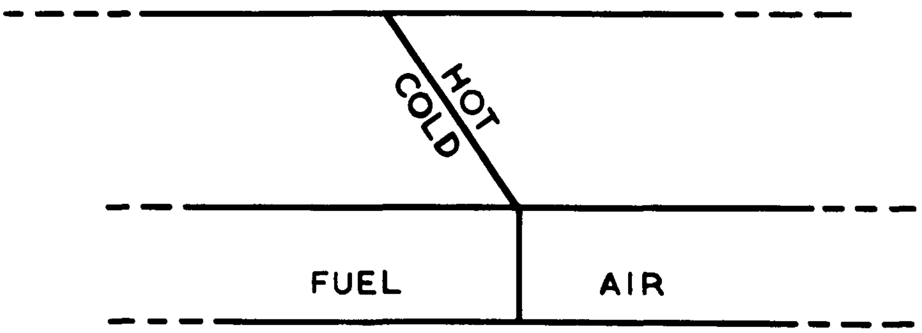
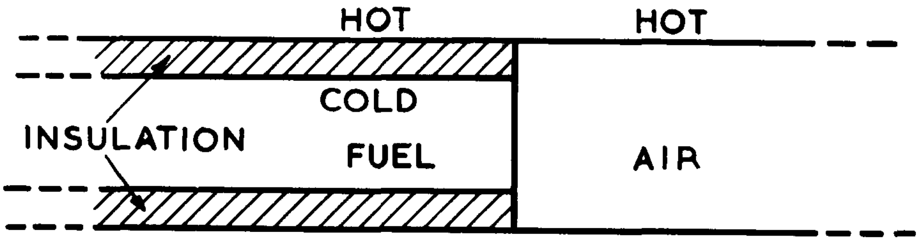


FIG.8 STRESSES IN HEATED HONEYCOMB SANDWICH

(a) UNINSULATED FUEL TANK



(b) FUEL TANK INTERNALLY INSULATED



(c) FUEL TANK IN EXTERNALLY INSULATED AIRCRAFT

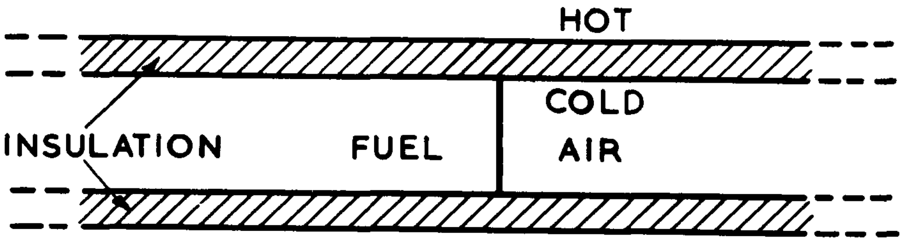


FIG.9(a-c) HEATING AT FUEL TANK BOUNDARIES

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The advantages and disadvantages of each method are noted and the effectiveness is illustrated in some cases by numerical examples. Mention is made of the stresses in honeycomb sandwich and at the boundaries of fuel tanks.

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