DERIVATION AND TEST OF ELEVATED TEMPERATURE THERMAL-STRESS-FREE FASTENER CONCEPT

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ABSTRACT

Future aerospace vehicles must withstand high temperatures and be able to function over a wide temperature range. New composite materials are being developed for use in designing high-temperature lightweight structures. Due to the difference between coefficients of thermal expansion for the new composite materials and conventional high-temperature metallic fasteners, innovative joining techniques are needed to produce tight joints at all temperatures without excessive thermal stresses. A thermal-stress-free fastening technique is presented that can be used to provide structurally tight joints at all temperatures even when the fastener and joined materials have different coefficients of thermal expansion. The derivation of thermal-stress-free fasteners and joint shapes is presented for a wide variety of fastener materials and materials being joined together. Approximations to the thermal-stress-free shapes that result in joints with low-thermal-stresses and that simplify the fastener/joint shape are discussed. The low-thermal-stress fastener concept is verified by thermal and shear tests in joints using oxide-dispersion-strengthened alloy fasteners in carbon-carbon material. The test results show no evidence of thermal stress damage for temperatures up to 2000°F and the resulting joints carried shear loads at room temperature typical of those for conventional joints.

INTRODUCTION

Future aerospace vehicles must withstand high temperatures and be able to function over a wide temperature range. New composite materials are being developed for use in designing high-temperature lightweight structures. Many of the high temperature structural composite materials have coefficients of thermal expansion (CTE) that are considerably different from those of high-temperature metallic fasteners. Thus, conventional high-temperature metal fasteners and fastening techniques do not provide structurally tight joints for the complete use temperature range without introducing severe thermal stresses that can result in premature failure. The difficulties in designing a tight structural joint for all temperatures are illustrated by the accompanying sketch and table. If the fastener material has a higher CTE than the material joined together, a standard cylindrical fastener which is snug at room temperature will produce high thermal stresses at elevated temperatures. If sufficient radial clearance is provided at room temperature to reduce the thermal stress at elevated temperature, the fastener will be loose in the radial direction at room temperature and loose in the axial direction at elevated temperatures. An axially snug joint at elevated temperature can be achieved by providing high clamping pre-stresses in the joint at room temperature but the high pre-stresses may be detrimental to the joint. Thus, new joining techniques are needed for the high-temperature composite materials.

A thermal-stress-free fastener concept has been developed at the Langley Research Center that can be used to provide structurally tight joints at all temperatures even when the fastener and joined materials have different coefficients of thermal expansion. The derivation of thermal-stress-free fasteners and joint shapes is presented herein for many combinations of fastener material and joined material. Approximations to the thermal-stress-free shapes that result in joints with low-thermal-stresses and that simplify the fastener/joint shape are discussed. Results of thermal and shear tests are also presented from an ongoing experimental program to verify a low-thermal-stress joint concept which consists of oxygen-dispersion-strengthened (ODS) alloy fasteners in carbon-carbon material.

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PROBLEM AREAS FOR CONVENTIONAL JOINTS IN HIGH-TEMPERATURE APPLICATIONS

Fastener coefficients-of-thermal expansion greater than that for joined materials
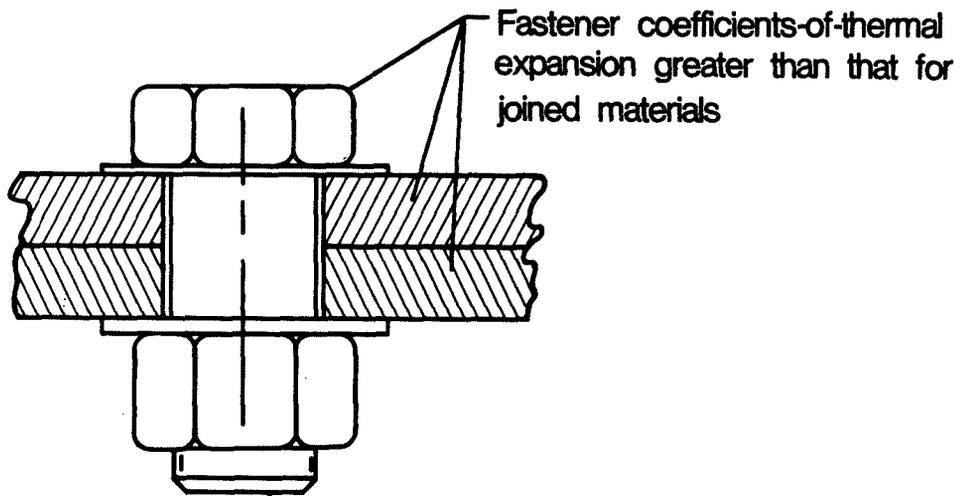
	Joint condition	
	Room temperature	Elevated temperature
Radial direction	Snug Loose	High thermal stresses Snug
Axial direction	Snug Pre-stressed	Loose Snug

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THERMAL-STRESS-FREE METAL FASTENER
CONCEPT FOR HIGH-TEMPERATURE JOINTS

The thermal-stress-free fastener concept (Ref. 1) is illustrated by the sketch. A typical high-temperature joint with a metal fastener joining material with a different CTE is shown. The metallic components of the joint consist of a conical fastener, washer, and nut. The remaining components of the joint consist of two plates and a washer made of the material being joined together. The thickness of the washer made from the same material as the plates is determined so that the origin (apex) of the conical fastener is located at the outer plane of the washer as shown. The inner diameter of the washer must have a clearance fit with the shank of the fastener if the CTE of the fastener is greater than the CTE of the material being joined. The clearance is determined by the difference between the coefficients of thermal expansion between the two materials and the temperature extremes for which the joint is designed. Because the metal fastener and the composite material have a different CTE, heating or cooling the joint results in different amounts of expansion for the two materials. However, if the fastener material and the material being joined both have an isotropic CTE, relative expansion or contraction between the fastener and the material takes place on radial lines projecting from the origin of the conical fastener. Thus, the expansion or contraction does not result in tightening or loosening of the joint and does not introduce thermal stresses into the material.

High-temperature
metal fastener

Material to be joined with
coefficient-of-thermal
expansion different from
fastener

Metal washer

Origin

Hex nut
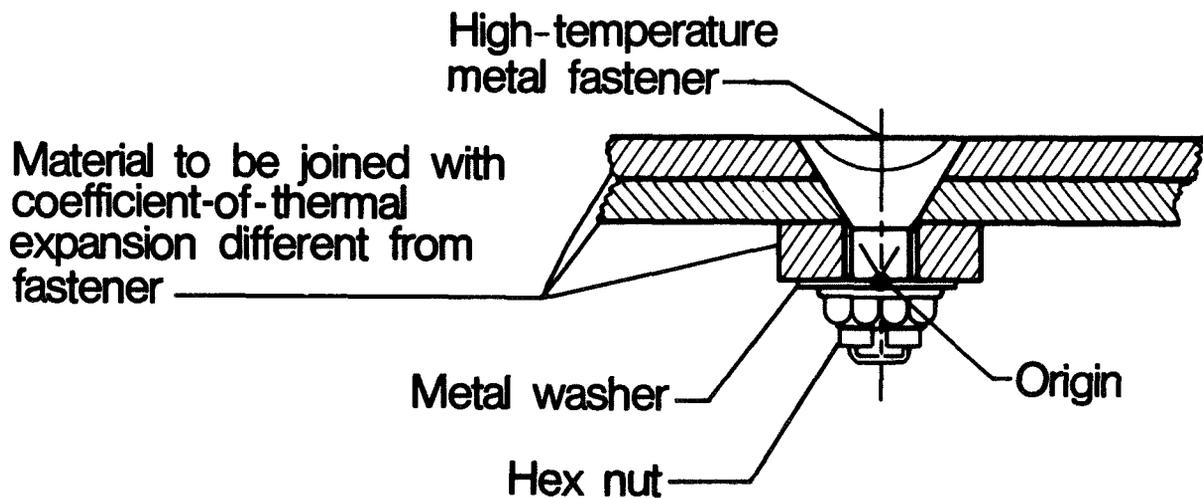
● Joint is thermal-stress-free if fastener and material being joined have isotropic coefficients-of-thermal expansion

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THERMAL EXPANSION OF THERMAL-STRESS-FREE CONCEPT

Thermal expansion relative to the origin for the thermal-stress-free concept is illustrated in the two sketches. The dashed lines show an exaggerated view of the expanded shapes assuming that the fastener has a higher CTE than the joined material. The larger expansion of the fastener is evident. For the joint with isotropic CTE (sketch on left), the thermal expansion does not result in any interference or clearance between the fastener and the joined material and does not have thermal stresses or become loose at the high temperatures. However, for the joint with the joined material having a non-isotropic CTE (sketch on right), there is an interference zone due to a reduction in the cone angle for the joined material. The change in cone angle is due to the inplane CTE being smaller than the CTE through-the-thickness for the joined material. (An inplane CTE larger than the CTE through-the-thickness would result in an increase in cone angle and therefore a loose fit at high temperatures.) Thus, for materials that do not have an isotropic CTE, the conical fastener configuration reduces but does not eliminate the thermal stresses. Since many of the high-temperature composite materials do not have isotropic CTE, a thermal-stress-free fastener configuration is needed that is applicable to materials that have different CTE in the inplane and through the thickness directions (specially orthotropic materials).

Isotropic CTE   **Non-Isotropic CTE**
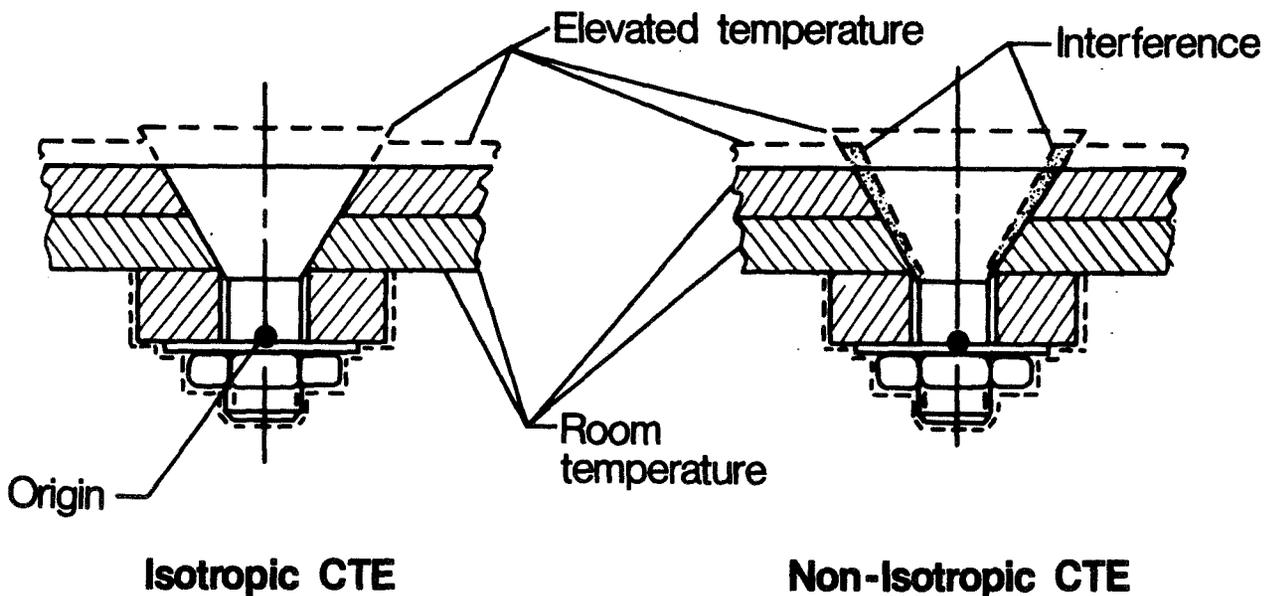
DERIVATION OF THERMAL-STRESS-FREE BOUNDARY

A general description of the shape of the thermal-stress-free boundary between the fastener material and the joined material is desired in which both materials have these specially orthotropic characteristics. Derivation of the desired thermal-stress-free boundary between the two materials requires an interface along which the two materials will remain in contact without interference or separation as temperature changes. The boundary between the two materials is illustrated in the sketch and is given by $y=f(x)$ at the initial temperature. The desired boundary is shaped so that, as the temperature is increased or decreased, points located on the boundary at the initial temperature may move relative to each other but must remain on a common boundary for all temperatures. The boundary may change shape with a change in temperature, as shown, but all points of both materials initially on the boundary will remain on the boundary. Such a boundary can be found if the following assumptions are made: the CTE is constant with temperature and location for both materials; the temperature is uniform in both materials; and there is no friction along the boundary. Derivation of the thermal-stress-free boundary is discussed in reference 2.
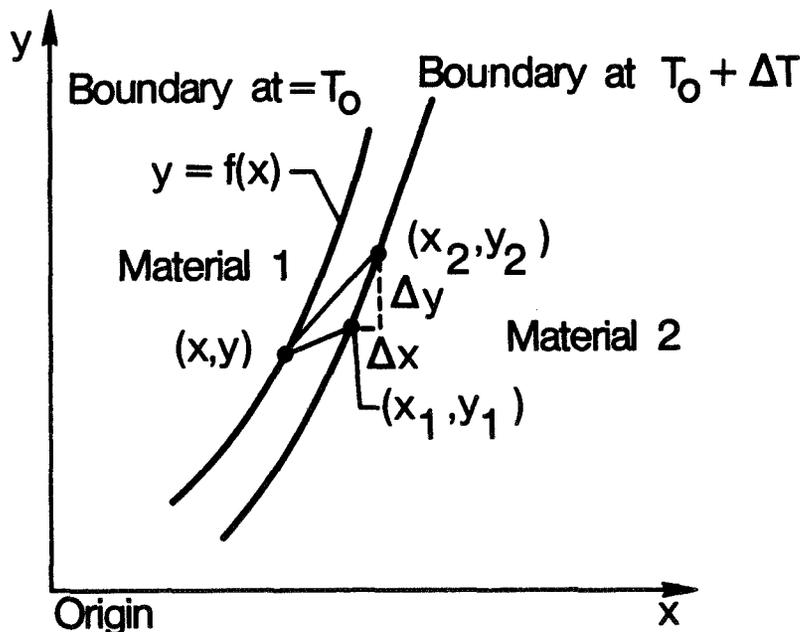
Assumptions

- CTE constant with temperature and location
- Uniform temperature
- No friction along boundary

THERMAL-STRESS-FREE BOUNDARIES

A family of thermal-stress-free boundaries exists and is given by the equation shown, where c is an arbitrary constant and p is the ratio of the differences between the CTE for the two materials in the through-the-thickness and the inplane direction. The value of c, although arbitrary for defining a family of thermal-stress-free boundaries, is determined by the fastener diameter and washer thickness when deriving a specific fastener shape. The family of thermal-stress-free boundaries is shown in the figure. The curvature of the different boundaries is determined by the relationship between the CTE of the two materials as defined by p. Each of the thermal-stress-free boundaries shown is derived in two dimensions but if the inplane CTE of each material is independent of direction, then the boundary can be rotated about an axis to produce axisymmetric thermal-stress-free fasteners. Note that for p=1, which would result for joints involving different isotropic materials, the thermal-stress-free boundary is a straight line which results in a conical fastener. Thus, the initial conical fastener concept discussed previously is a subset of the thermal-stress-free boundaries given above.

$$y = cx^{p} \quad ; \quad \text{where } p = \frac{\alpha_{y1} - \alpha_{y2}}{\alpha_{x1} - \alpha_{x2}}$$

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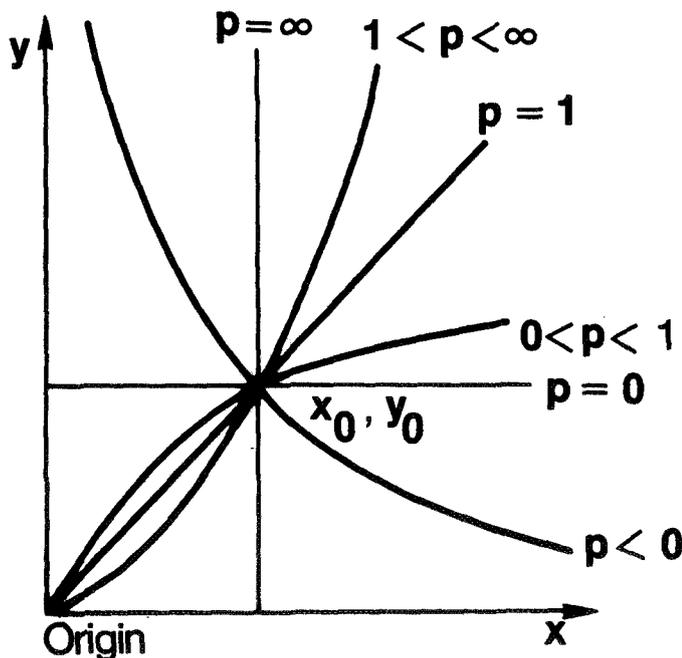
TYPICAL THERMAL-STRESS-FREE FASTENER CONFIGURATIONS

Typical thermal-stress-free fastener configurations which utilize the derived thermal-stress-free boundaries are shown in the figure. The fastener configurations shown for p greater than zero appear practical to use for making conventional joints. For p between 0 and 1, the fastener has a concave shape; whereas, for p greater than 1 it has a convex shape. As pointed out previously, a value of p equal to 1 results in a conically shaped fastener. Note that if the diameter of the cylindrical portion of the fastener is maintained fixed as shown, the washer thickness varies widely depending on the value of p. A clearance between the washer and the shank of the fastener must be maintained at all temperatures to avoid thermal stresses. For values of p less than zero, the thermal-stress-free boundaries do not result in a conventional joint configuration. The sketch shows one possible thermal-stress-free configuration for the case where p is less than zero. The configuration shown is rather inefficient as the joint shear load would have to be carried in bending of the fastener. However, the joint is thermal-stress-free and may be the only joint configuration possible for certain combinations of materials. An example of high-temperature materials that would require such a fastener is graphite/polyimide (Gr/PI) materials being joined together by a high-temperature metal fastener. The negative value of p is due to the difference in in-plane and through-the-thickness CTE for Gr/PI being large and the CTE for the fastener being between the two values for Gr/PI. Most other high-temperature composite materials and metal fastener combinations have positive values of p which result in more practical thermal-stress-free configurations.

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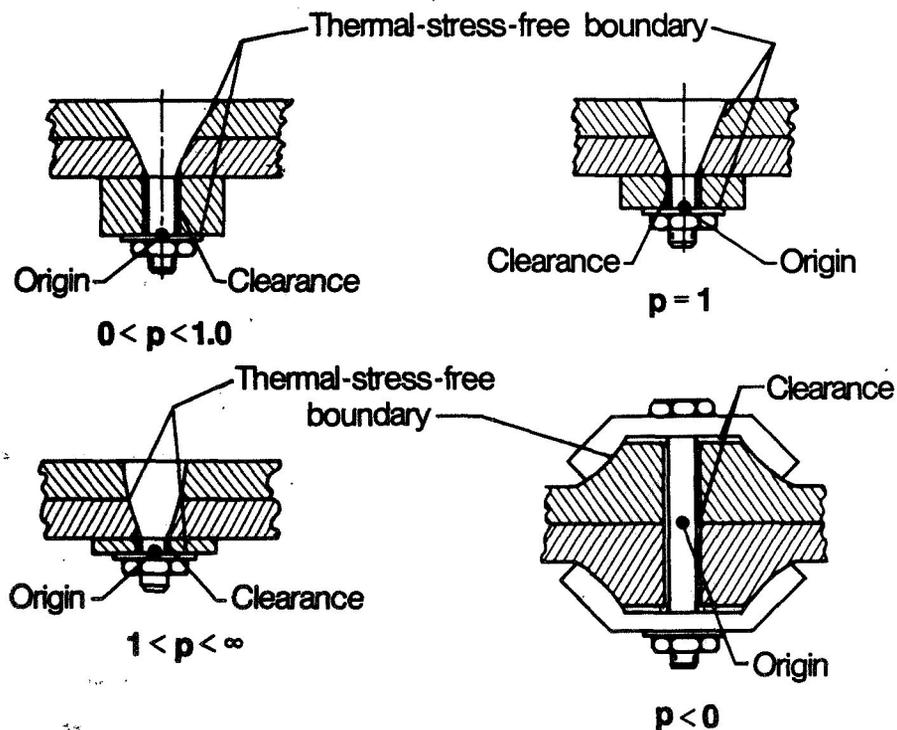
EFFECT OF DESIGN PARAMETERS W AND R ON FASTENER PROPORTIONS

The thermal-stress-free boundary for a particular fastener configuration is determined by the constant c and by the relative values of the CTE for the fastener and the materials joined together. The constant c is determined from two design parameters --the washer thickness W and the radius r of the cylindrical portion of the fastener by the relationship $c = W/R^p$. The effect of changes in these two parameters on the fastener and joint configuration is shown in the figure for a typical combination of materials (p=constant). The baseline fastener configuration is shown in the sketch in the center of the figure. Increasing the radius of the fastener while keeping the washer thickness constant (decreasing c) results in a fastener with a much larger head as shown in the sketch in the upper left-hand corner of the figure. Increasing the washer thickness and keeping the radius constant (increasing c) results in a fastener with a much smaller head as shown in the sketch in the lower right-hand corner of the figure. Changing both the radius and the washer thickness results in a wide variation of possible fastener configurations and gives the designer a wide range of choices in determining the desired fastener joint configuration.
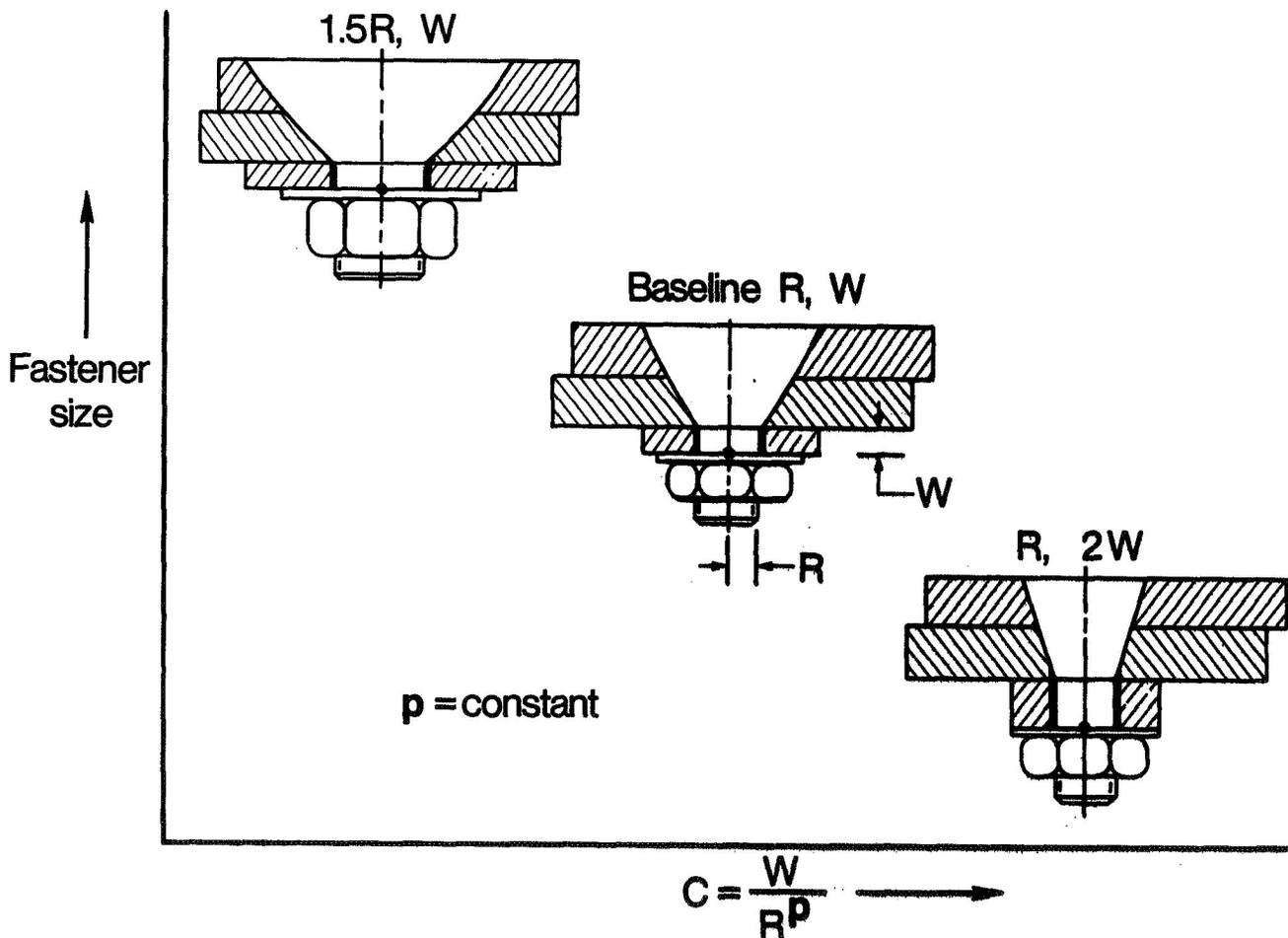
THERMAL-STRESS-FREE FASTENER FOR CARBON-CARBON MATERIAL

A thermal-stress-free fastener design for an ODS alloy fastener joining two pieces of carbon-carbon material together is shown in the sketch. Each plate of carbon-carbon material is 0.15-inch thick and the diameter of the shank of the fastener is 0.25 inch. The thermal-stress-free boundary is the curved solid line indicated on the sketch. A relatively thick carbon-carbon washer is required to properly position the origin, of the thermal-stress-free boundary.

Due to the difficulty of machining a fastener with the curved thermal-stress-free shape, it is desirable to simplify the shape as much as possible without destroying the low-thermal-stress properties of the joint. The curved shape can be approximated by a straight line as shown which results in a conically shaped fastener and hole. For the fastener configuration shown, the straight line approximation results in a maximum deviation of 0.005 inch from the curved thermal-stress-free boundary and thus should still result in a low-thermal-stress joint. Note that to approximate the thermal-stress-free fastener configuration with a conical fastener, the washer thickness is determined by the origin of the thermal-stress-free boundary and not that of the origin of the cone. The location of the origin of the conical fastener is offset inside the free surface of the washer as shown. Thus, by simply off-setting the origin, conical fasteners, which are considerably less expensive to machine and much easier to apply than curved thermal-stress-free fasteners, can probably be used for many other combinations of materials and still give joints that have low-thermal-stresses when heated or cooled. A thermal stress analysis is needed to investigate the stresses introduced by making the conical approximation for various combinations of materials.

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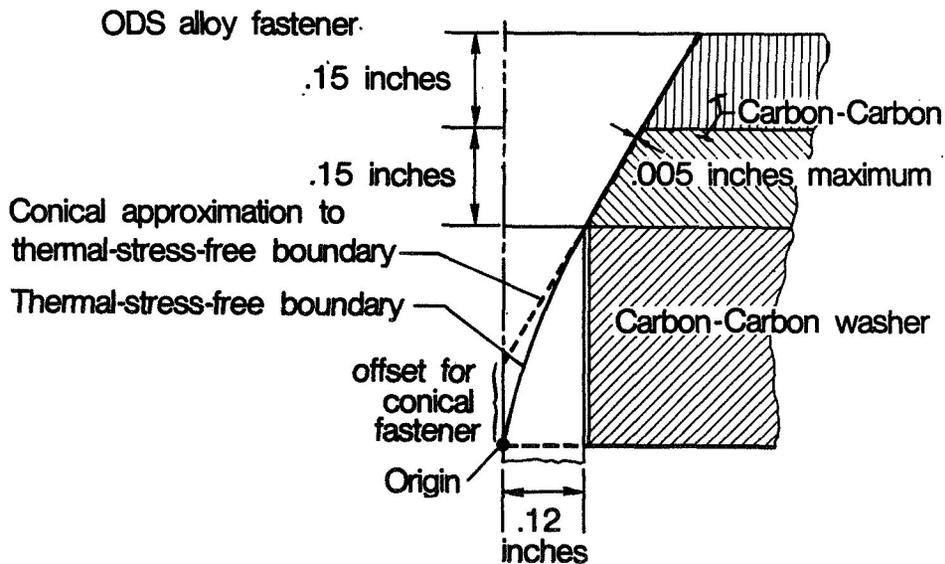
CARBON-CARBON LOW-THERMAL-STRESS JOINT TEST SPECIMEN

A test program was initiated to verify the low-thermal-stress concept using ODS alloy conically shaped fasteners in carbon-carbon material (see Ref. 3). Twelve specimens were tested, one of which is shown in the photograph. The specimens consist of two carbon-carbon plates connected by a single line of three low-thermal-stress fasteners. Three specimens each of four design configurations were tested. The configurations were chosen to represent typical structural joints and included various plate thicknesses and load transfer levels. The plates for the four joint designs contained the following number of plies of fabric: 7/8, 10/11, 11/18, and 18/21. The joint configuration at each fastener location consisted of an ODS-alloy metal fastener which passed through the two carbon-carbon plates, the carbon-carbon washer, and the ODS alloy metal washer and nut. The fastener had a 60 degree included-angle conical head and a number 10 machine screw threaded shaft. As previously mentioned, in approximating the thermal-stress-free configuration, the origin of each conical fastener was offset slightly inside the outer surface of the carbon-carbon washer.

The specimens were manufactured by Vought Corporation using their standard process for ACC-4 (four densifications) cross-ply (alternate layers of 0 and 90 degree fabric) material. The specimens were machined and then given a silicon carbide coating, followed by a Tetraethyl Orthosilicate high-temperature sealer and an LB (Vought Corporation designated for proprietary sealer) low-temperature sealer. After the coating and sealers were applied, the conical fastener holes were lightly reamed to provide good fit for the fasteners.

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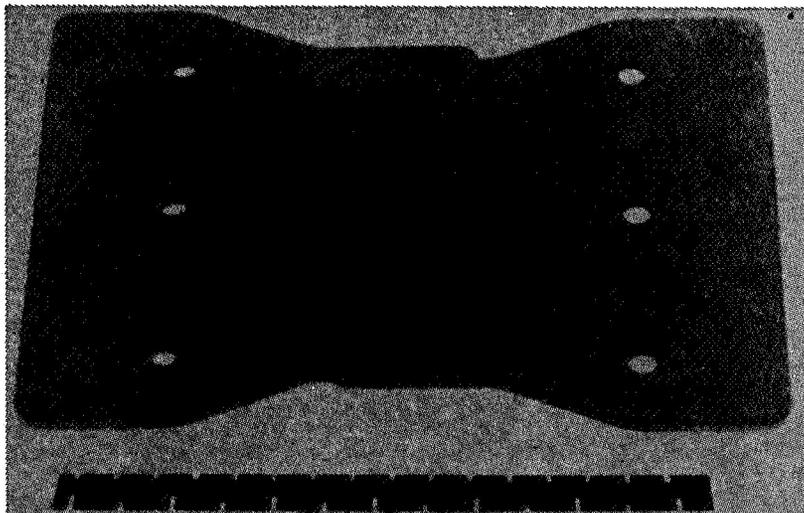
CARBON-CARBON LOW-THERMAL-STRESS CONICAL FASTENER TEST PROGRAM

The test program consisted of thermal-cycle tests and shear load tests. One specimen was subjected to a thermal cycle with no mechanical loading, ten specimens were tested to failure in shear at room temperature, and the other specimen was subjected to both a thermal-cycle test and a shear-to-failure test at room temperature. The specimens were assembled with the fasteners torqued to 5 in-lbs for each test.

The thermal tests consisted of drying the specimen at 250°F and 0.005 mm of mercury pressure for 12 hours and then heating to 2000°F and holding at that temperature for one hour in an oxidizing atmosphere. The atmospheric pressure for the specimen was gradually increased from 0.005 mm to 27 mm of mercury during heatup of the specimen and was maintained at that pressure for the remainder of the test. The specimen was then cooled and inspected for cracks or visual surface damage. Neither of the thermally cycled specimens showed any evidence of damage or cracking as a result of thermal stresses. Although the joints were not checked to determine if they maintained contact at the high temperatures, the behavior of the fasteners appears to be as expected.

● THERMAL CYCLE

    ● 2000° F FOR ONE HOUR

    ● .04 ATMOSPHERE PRESSURE

● SHEAR LOAD TESTS

SHEAR TEST SETUP FOR CARBON-CARBON LOW-THERMAL-STRESS JOINTS

For the shear tests, attachment brackets were bolted to each carbon-car-
bon sheet as shown in the sketch. The test specimen assembly was mounted in a
hydraulic universal test machine and loaded in tension to failure at a
constant displacement rate of 0.05 in./minute. The tension load applied a
linear shear load through the center of the row of fasteners and failed the
specimens in shear. The tests were conducted at ambient temperature and
pressure. Load was recorded as a function of crosshead displacement using an
X-Y recorder.

THERMAL-STRESS-
FREE FASTENER

TEST SPECIMEN

LOAD ATTACHMENT BRACKET
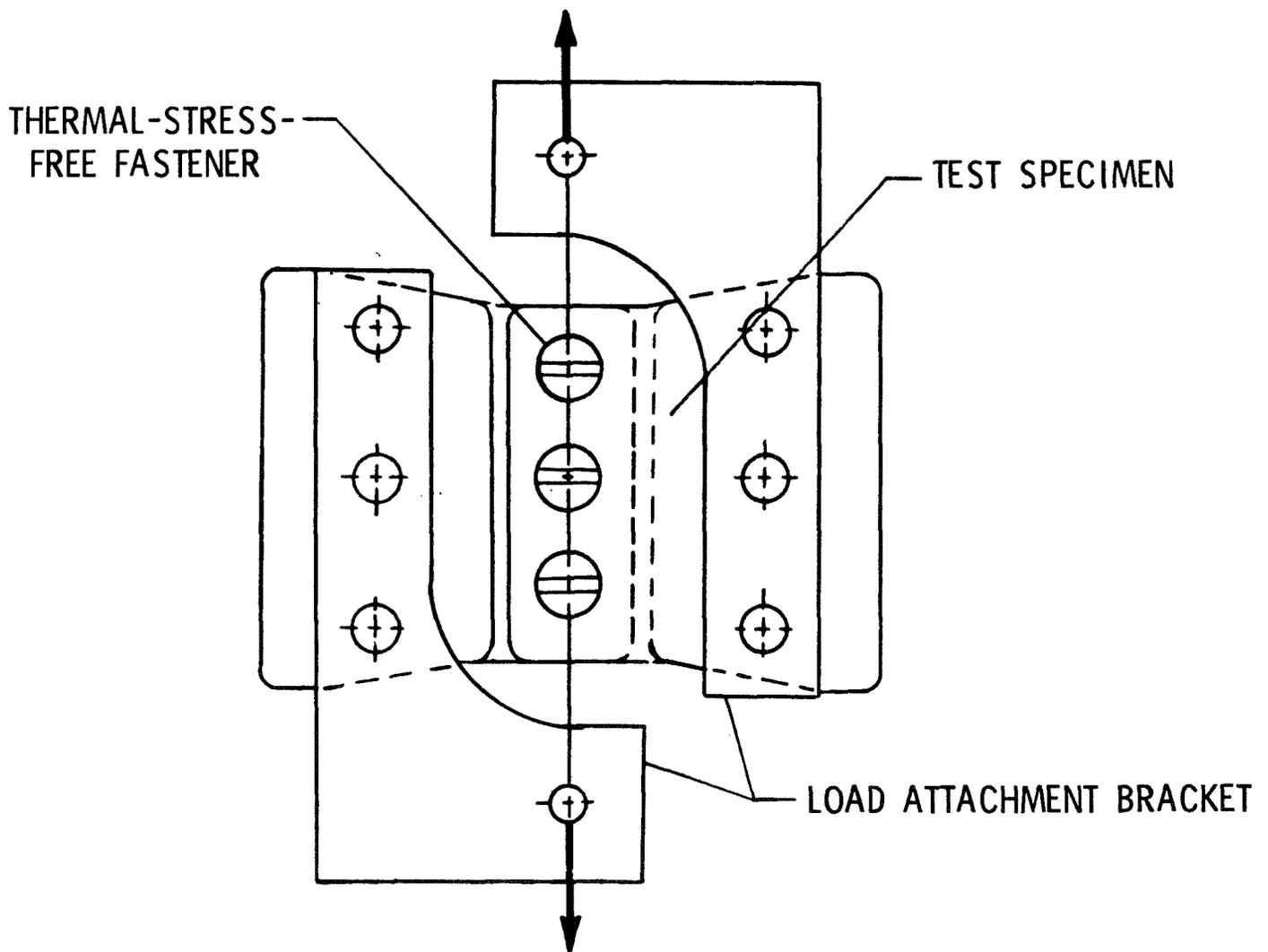
TYPICAL SHEAR FAILURE MODE FOR CARBON-CARBON LOW-THERMAL-STRESS JOINT

A typical shear failure mode for the specimens is shown in the figure. Joint failure results in bulging of the carbon-carbon material near the conical bolt head and under the carbon-carbon washer, rotation of the fasteners, and cracking of the carbon-carbon washer.
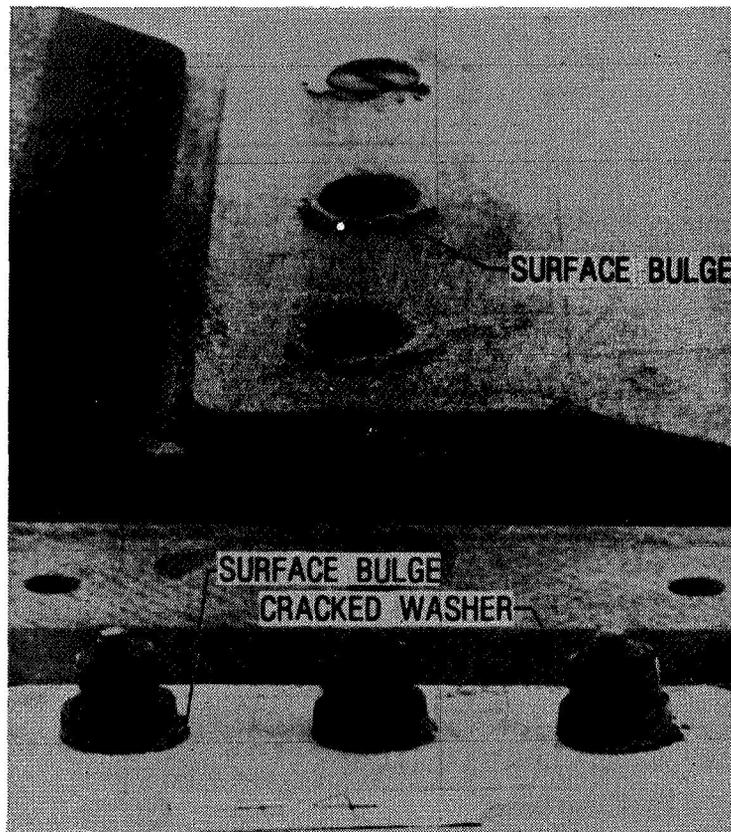
CROSS SECTION OF FAILED CARBON-CARBON LOW-THERMAL-STRESS JOINTS

The shear specimens all failed in the same manner. A cross-section view of a typical failed joint is shown in the photographs. Joint failure is thought to occur as follows: bearing failure occurs at the locations indicated by the arrow thus allowing fastener rotation and localized shear crippling failure to occur at the bearing failure points. Additional loading causes the failed zone to propagate circumferentially around the fastener and along a line from the bearing failure point to the free edge of the plate. Observation of the test indicates that the maximum strength of the joint is obtained approximately when the shear failure reaches the surface as indicated by a bulging of the carbon-carbon material near the head of the fastener and under the carbon-carbon washer. The displacement of the material under the washer applies a moment to the carbon-carbon washer until it cracks.
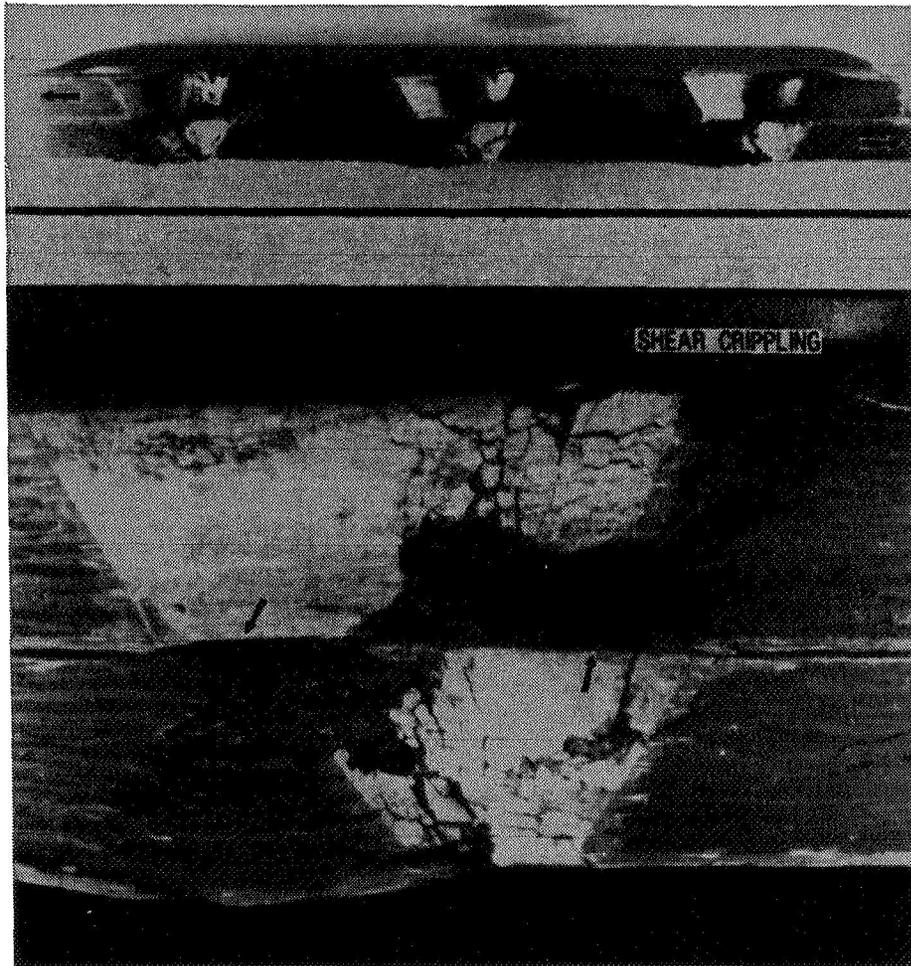
SHEAR STRENGTH OF CARBON-CARBON LOW-THERMAL-STRESS JOINTS

Relative shear strengths for the specimens are shown in the figure as a function of the number of plies in the plate subject to the highest bearing stress (thinner plate in each case). The solid line is a predicted bearing failure strength based on bearing ultimate strength obtained from cylindrical bolt bearing tests. The bearing failure criteria are reasonably accurate to predict the failure loads. For the thicker joints, the bearing failure criteria predict failure loads slightly higher than those obtained experimentally. Cross-section cuts through the center of the joint did not show any significant difference in failure modes for the different thickness specimens. The good agreement with the bearing failure criteria and the observed failure modes indicates that the low-thermal-stress joints have failure modes and strengths similar to conventional joints. One of the specimens that was thermally cycled was also tested to failure in shear at room temperature and is shown on the figure by the triangle symbol. Thermal cycling the joint did not have a significant effect on the joint strength nor on the failure mode.
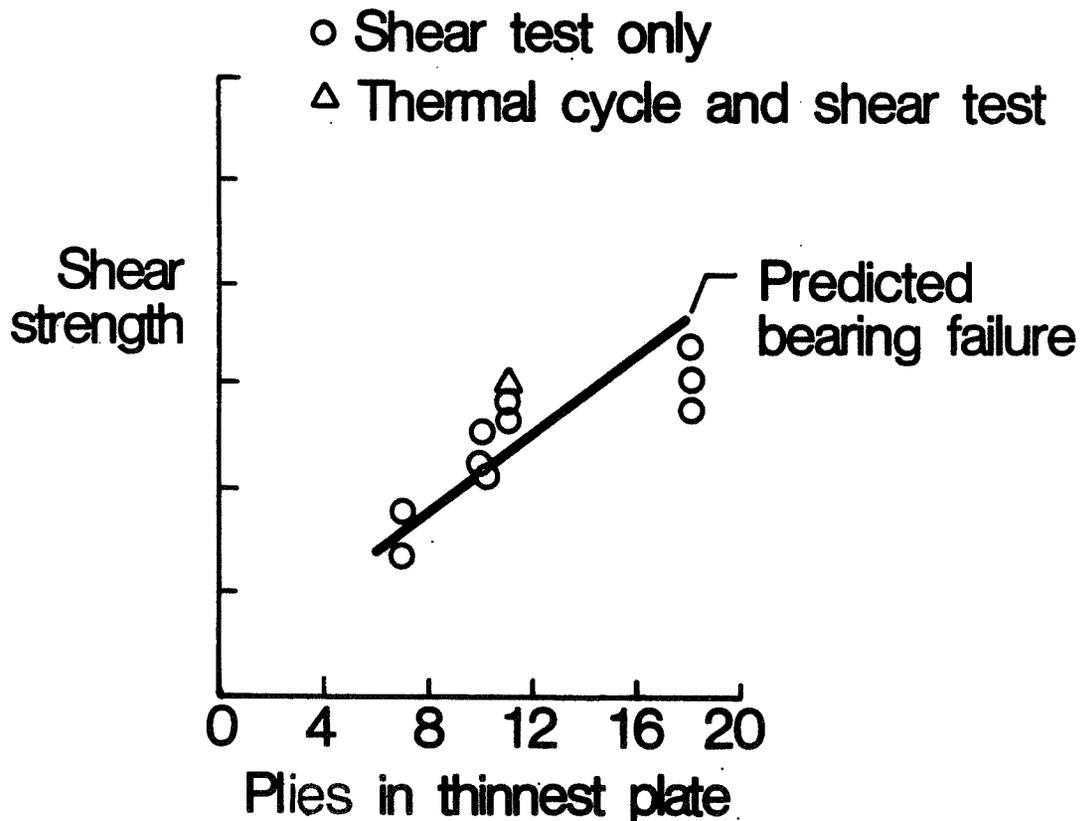
SUMMARY

Future aerospace vehicles must withstand high temperatures and be able to function over a wide temperature range. New materials are being developed for use in designing high-temperature lightweight structures. Due to the differences in coefficients of thermal expansion for the new materials and conventional high temperature metallic fasteners, innovative joining techniques are needed to produce tight joints at all temperatures without excessive thermal stresses. The thermal-stress-free fastening technique presented here can be used to provide structurally tight joints at all temperatures even when the fastener and joined materials have different coefficients of thermal expansion. The derivation of thermal-stress-free fasteners and joint shapes is presented for many combinations of fastener material and material being joined together. Approximations to the thermal-stress-free shapes that simplify the fastener/joint shape and that should result in joints with low-thermal-stresses are discussed. The low-thermal-stress fastener concept is verified by thermal and shear tests in joints using ODS alloy fasteners in carbon-carbon material. The test results show no evidence of thermal stress damage for temperatures up to 2000°F and the resulting joints carried shear loads at room temperature typical of those for conventional joints. Static failure strengths for the low-thermal-stress joints are predictable using bearing failure strengths and the failure modes are typical of those for conventional fasteners.

SUMMARY

- Thermal - stress -free fastener concept presented

- Fastener configuration determined by analysis

- Conical approximation to thermal - stress - free fastener shape with offset origin may be adequate for many materials

- Conical concept verified by thermal and shear tests

- Static failure strength of joints using conical fastener predictable using bearing failure strength

REFERENCES

1. Jackson, L. R.; Davis, Randall C.; Taylor, Allan H.; McWithey, Robert R.; Blosser, Max L.: DAZE Fastener, Inserts, Bushings. NASA Tech Brief LAR-13009, August 1983.

2. Blosser, Max L.; McWithey, Robert R.: Theoretical Basis for Design of Thermal-Stress-Free Fasteners, NASA TP-2226, November 1983.

3. Sawyer, James Wayne: Experimental Evaluation of Thermal-Stress-Free Fastening Technique for Two-Dimensional Carbon-Carbon Structures. Presented at Fifth JANNAF Rocket Nozzle Technology Meeting, Colorado Springs, Colorado, Dec. 6-8, 1983.