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RESIDUAL THERMAL STRESS CONTROL IN COMPOSITE REINFORCED METAL STRUCTURES*

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INTRODUCTION

Advanced composite materials, composed of boron or graphite fibers and a supporting matrix, make significant structural efficiency improvements available to aircraft and aerospace designers. Numerous developmental programs are being conducted throughout the industry to utilize this potential. Some of these programs are described in Reference 1.

Two distinct design philosophies have been developed as a result of various study programs: all composite construction and composite reinforced metal construction. The approach selection may be made on the basis of cost effectiveness, as determined through consideration of weight saving, the value of saving weight, and the raw material and fabrication costs. The inter-relationship of these factors is shown in Figure 1. Composite effectiveness factor (CEF) is defined as the ratio of weight saved to weight of composite used. Typically, all composite construction has a CEF of one while reinforced structures achieve two and higher. From Figure 1 it can be seen that high CEF values of reinforced construction translate to cost effective applications at an earlier date than all composite construction, especially at low values of weight saving.

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The weight saving potential of several reinforcing concepts was explored during Phases I, II, and III of NASA Contract NAS1-8858, and the results are reported in References 2, 3, and 4. Boron-epoxy composite was employed to reinforce metallic elements of aluminum and titanium. The reinforcement was joined to the metallic elements by adhesive bonding. During Phase I of this program the occurance of thermally induced residual stresses in the bonded assemblies was demonstrated.

Residual stresses occur when conventional elevated temperature adhesive bonding procedures are employed and the materials being joined have unequal coefficients of thermal expansion. Adhesive systems which cure at elevated temperatures are commonly employed to produce structurally adequate joints. Typical cure cycles are shown in Figure 2. The residual stresses occur because components of the assembly are brought together at room temperature, enclosed in a vacuum bag, and heated to the curing temperature in an oven or autoclave. During the heating process, thermal growth of each component proceeds without restriction. If the coefficients of linear thermal expansion are different, differing amounts of thermal growth occur. The bond between the components is established near the curing temperature and any subsequent temperature change, such as cooling to room temperature, will induct thermal stress, since the components are mutually restrained from expanding or contracting at their individual rates.

The residual stress level produced in composite reinforced metal structures is a function of cross-sectional area, modulus of elasticity, and coefficient of thermal expansion of the components and the temperature change from the temperature at which the components were stress free. The expansion coefficients of aluminum and composite materials are such that residual tension stresses are produced in the aluminum constituent after conventional adhesive bonding. The resulting stress levels are depicted in Figure 3. These residual tension stresses could adversely affect structural static strength and fatigue life.

Investigation, suggested by NASA, indicated that the residual stress level could be reduced through suitable modification to the manufacturing procedures employed during the adhesive bonding process. This program was initiated to evaluate the capability to reduce these residual stresses and to explore several approaches to achieve this control. A portion of the results of this program are discussed in this paper. Additional information may be found in Reference 5.

STRESS ALLEVIATION METHODS AND SPECIMENS

If composite reinforced metal assemblies are to be free of residual stresses at room temperature then they must be stressed when heated or cooled to any other temperature. This includes the temperature at which the adhesive bond between components of the assembly is established. It follows that bonded assemblies which are produced at elevated temperature will be stress free at room temperature if, during bonding, the components of the assembly are stressed to the appropriate level. These stress levels are predictable utilizing the relationships developed in Reference 6. During this program nine assembly methods, listed in Table 1, were employed to produce the desired stress distributions during the adhesive bonding process to control the residual stress level.

Assembly methods 1 and 2 (method designation taken from Table 1) utilized the self equilibrating nature of thermal stresses in bi-material assemblies to achieve mechanical constraint. The metal and composite components of the assembly were joined at the desired stress free temperature with mechanical fasteners. The adhesive bonding material, uncured, was placed between the components prior to the installation of the fasteners. As the mechanically joined components were heated to cure the adhesive, each component attempted to expand at its own rate. This free expansion was prevented by the strain continuity imposed by the mechanical fasteners and equal but opposite forces were established within the components.

Subsequent cooling to room temperature was then accomplished with the same strain compatibility imposed by both the established adhesive bond and the mechanical fasteners. Since the components of the assembly were unstressed when they were mechanically joined and relative thermal growth was prevented during the bonding cycle, the resulting assembly is free of residual stress when it is returned to room temperature.

For assemblies which are not symmetric, the equal and opposite forces which occur during the cure cycle will produce an internal bending moment. In the absence of suitable constraint this bending moment will produce deflection so that equilibrium is maintained. This was the case with assembly method 1. The assembled components were enclosed in a vacuum bag, called an "envelope bag", which surrounded the assembly, permitting bending deflection to occur freely.

In contrast, assembly method 2 utilized a supporting tool to prevent deflection due to internal bending moment. The components were assembled, using mechanical fasteners, as described above. This assembly was then placed on a supporting tool and the vacuum bag was installed over the parts and sealed to the tool. Autoclave pressure over the vacuum bag surface provided the forces required to hold the component parts flat against the tool surface.

The stress levels which occur within the components when assembled by methods 1 or 2 are determined by the physical properties of the components and the relative cross sectional areas.

If a large piece of composite is to be joined to a relatively small section of aluminum, the stress level in the aluminum will be high. Since this stress occurs at elevated temperature where yield strength is reduced, failure in the metal might result. This potential limitation is overcome by mechanically fastening both the composite and the metal component to a relatively stiff tool made of a material having a coefficient of thermal expansion about midway between the expansion coefficients of the assembly constituents. This approach was designated method 3. The expansion coefficients of aluminum and either boron or graphite composite are such that steel is a reasonable choice for tooling material. By fastening both assembly components to the steel tool, both components are forced to expand with the tool. Also, the stress level in the components during cure becomes a fixed value for all cross-sectional areas as long as the steel tool is substantially stiffer than either component.

The degree of control of stress levels which occur during the curing cycle is maximized through the use of preloading. This capability was explored through assembly methods 4, 5, and 6. At the curing temperature, the stress state of the components which is required to achieve a residual stress free assembly may be translated into a strain difference between the components. The stress level in either the composite or the metal component during the cure cycle may be arbitrarily selected, subject only to the requirement that inelastic deformation does not occur. By maintaining the correct strain difference between the components through adjustment of the applied load on the second component the completed assembly can be produced with no residual stress.

Assembly method 4 utilized the above approach to maintain the composite detail stress-free at all times. The metal component of the assembly was preloaded and constrained in this state by the tool. The required preload level, which determined strain, was computed based upon the required strain difference and the thermal expansion characteristics of the tool and the aluminum component. The preloaded aluminum was constrained to the tool by mechanical fasteners or by confining the metal component in a cavity within the tool. The cavity confinement approach was very convenient for assemblies which required the aluminum component to be preloaded in compression.

The preloading technique also makes it possible to produce assemblies which are free of residual stress at temperatures other than room temperature. This condition may be desirable for certain combinations of vehicle loads and temperatures. Adjusting the strain difference between the components of the assembly achieves the desired result. This can be done by method 4, which eliminates stress on the composite component, but this may induce prohibitively high stress levels in the metal component. Assembly methods 5 and 6 caused both components to be stressed. With assembly method 5, the metal component was preloaded and then both components were fastened to the tool. For assembly method 6 both components were preloaded (each to a different strain level) and then restrained by the tool. These techniques produced lower metal stress levels and higher composite stress levels during the cure cycle than would have occurred using assembly method 4.

Assembly method 7 was another technique employed to produce assemblies free of residual stress at a preselected temperature between the assembly temperature and the cure temperature. Both components were fastened to a steel tool but provision was made for a limited amount of free thermal expansion of one component prior to the introduction of mechanical constraint by the tool. This was accomplished by using oversize bolt holes in the metal detail.

Assembly method 8 utilized the thermal growth behavior of the aluminum component to accomplish the preloading. The metal details were cooled, causing contraction, and then placed in a cavity type tool. The length of the cavity was accurately controlled so that upon reheating to room temperature the desired amount of preload had been established. As with assembly method 4, the preload was selected so that the composite detail was unstressed during the adhesive bonding operation.

The final assembly method employed during this study was designed to control the thermal growth of the aluminum detail through continuous support on the tool rather than at the end of the part as was done with mechanical fasteners. The tool was made of fiberglass reinforced polyester. This material was selected because its coefficient of thermal expansion ($2.3 \times 10^{-6}/°F$) is close to the expansion coefficients of the composite materials. The aluminum component was bonded to the tool using a room temperature curing adhesive. Then the composite details were mechanically fastened to the aluminum and bonded. The fiberglass tool was then removed from the assembly by peeling the tool laminations.

The specimen configurations for this program were selected to be representative of potential aircraft structural applications. These included reinforced flat sheets, simulating fuselage and wing skins; hat stiffeners, which are employed in the fuselage; and zee section stiffeners, as are found in wing construction. The flat sheets and hat stiffeners were made of 7075 alloy aluminum and the zee stiffeners were 7178 alloy aluminum extrusions. All metal components were heat treated to the T6 condition. Figures 4 through 6 show representative specimens used in the study.

Composite materials used in this program were SP-272* boron-epoxy and SP-286* graphite-epoxy employing Modmor Type II graphite. Unidirectional laminates five and four plies thick (respectively) were fabricated, cured, and slit to the required width. These strips were stacked and bonded to produce the desired amount of reinforcement. In this way the ratio of composite area to total area (see Figure 3) was varied during the program.

*Available from Minnesota Mining and Manufacturing Company.

Adhesive systems employed for both the second stage composite bonding and for composite to metal bonding were AF-126* and AF 30*. These adhesive systems cure at 250°F and 350°F respectively, producing the two levels of residual stress shown in Figure 3 when conventional bonding practices are employed. Secondary bonding of composite elements was achieved using the same adhesive system and cure temperature which was used for the composite to metal bond.

The reduction in residual stress which was achieved with the various specimens and assembly methods was determined by measuring the strain induced in the components during fabrication. Strain was determined by measuring the distance between two scribed lines spaced approximately ten inches along the length of the specimen. Each component of an assembly was clamped flat and the initial distance between the marks was determined on an optical bench as shown in Figure 7. Following the adhesive bonding cure cycle these distances were remeasured, and from the change in length, strain and stress level were computed. Strain due to preload was also verified in this manner by measuring the distance between the marks before and after load application.

RESULTS

Representative results are shown in Figures 8, 9, 10, and 11, where the achieved residual stress levels in the aluminum components are shown as a function of the geometry parameter composite area/total test area. Figures 8 and 9 show results obtained with those specimens bonded with the adhesive system which cured at 250°F. The results shown in Figures 10 and 11 are for those specimens bonded at 350°F. All specimens in these groups were designed to be stress free at 70°F, resulting in stress producing temperature differences of 180°F and 280°F. For comparison, predicted residual stress levels which occur due to conventional bonding techniques are also shown.

*Available from Minnesota Mining and Manufacturing Company.

As can be seen in Figures 8 through 11, residual stress level was significantly reduced for both adhesive curing temperatures and for both boron and graphite reinforcement. The amount of residual stress reduction achieved was independent of the composite to metal ratio.

The results obtained with the individual assembly methods are compared in Figure 12. For each assembly method the average reduction in residual stress, expressed as a percent of the objective reduction, is shown. Assembly method 4, which employed preloading the metal component such that the composite reinforcement was not loaded, was the most successful. The average reduction of residual stress was slightly in excess of 100 percent, indicating that in some cases the preload level was more than desired. This was also the case with method 8, which employed cooling and confinement rather than mechanical means to achieve preloading.

Assembly method number 7 was not successful. This method required a limited amount of free thermal growth before constraint was applied, and this free growth did not occur. It is suspected the growth was prohibited by frictional forces.

All other methods, while not as successful as method 4, demonstrated significant potential with results within ± 30 percent of the objective.

Potentially significant creep deformation was consistently observed in the aluminum components of the assemblies cured at 350°F. This deformation, shown in Figure 13, was found to be a function of the stress level in the metal component at the cure temperature. The 7178-T6 aluminum alloy experienced larger creep deformation than 7075-T6 aluminum at comparable stress levels. Since these deformations were determined from bonded assemblies, two verification tests were performed. In these tests an aluminum component was confined in a tool and subjected to a cure cycle as had been used to fabricate the bonded assemblies. These results, also shown in Figure 13, substantiated the previous results. Creep deformation was not consistently observed in the assemblies bonded at 250°F.

CONCLUSIONS AND RECOMMENDATIONS

The results obtained during this study indicate that residual stress induced during bonding of composite reinforcement to metal structural elements can be reduced or eliminated through suitable modification to the manufacturing processes. The most successful method employed during this program used a steel tool capable of mechanically loading the metal component in compression prior to the adhesive bonding cycle.

Compression loading combined with heating to 350°F during the bond cycle can result in creep deformation in aluminum components. The magnitude of the deformation increased with increasing stress level during exposure to 350°F.

Additional developmental work is desirable to refine and scale-up the assembly methods of this study for production. Creep behavior and the effects of creep deformation upon other parameters such as fatigue life should be defined. The extension of these concepts for residual stress alleviation should be accomplished for multidirectionally oriented composite reinforcement.

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LIST OF ILLUSTRATIONS

1	MECHANICALLY JOIN COMPONENTS NO SUPPORTING TOOL
2	MECHANICALLY JOIN COMPONENTS SUPPORT ON TOOL OR CAUL PLATE
3	MECHANICALLY JOIN COMPONENTS TO TOOL
4	PRELOAD METAL DETAIL AND CONSTRAIN BY TOOL COMPOSITE COMPONENT NOT RESTRAINED
5	PRELOAD METAL DETAIL AND MECHANICALLY FASTEN ALL COMPONENTS TO TOOL
6	PRELOAD ALL COMPONENTS AND MECHANICALLY FASTEN ALL COMPONENTS TO TOOL
7	MECHANICALLY FASTEN COMPONENTS TO TOOL BUT ALLOW FOR LIMITED FREE THERMAL GROWTH OF METAL COMPONENT
8	PRELOAD METAL DETAIL BY COOLING AND RETAINING IN TOOL
9	BOND METAL DETAIL TO TOOL HAVING LOW COEFFICIENT OF EXPANSION MECHANICALLY FASTEN COMPOSITE DETAIL TO METAL DETAIL

TABLE 1 ASSEMBLY METHODS

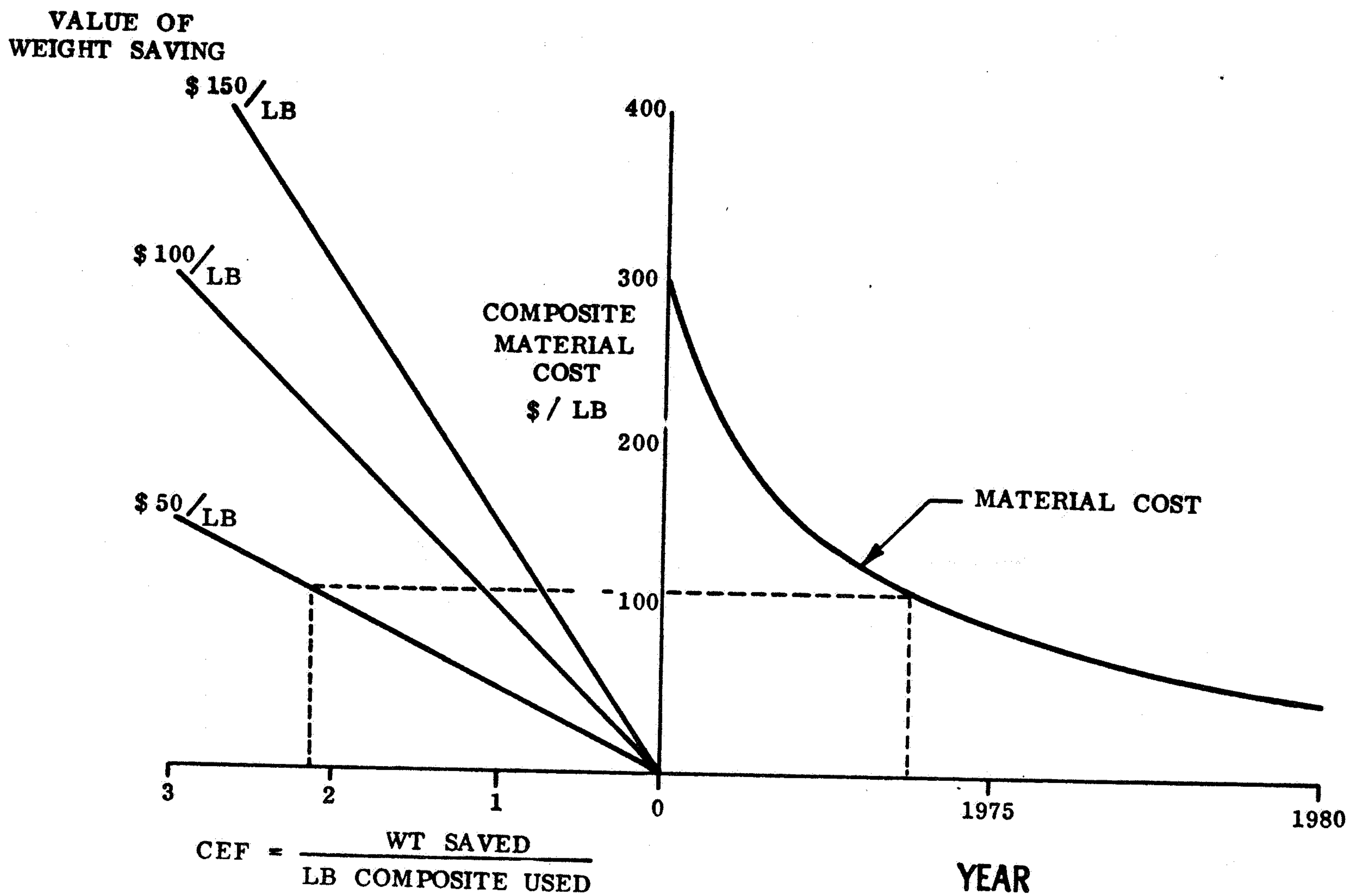

FIGURE 1 COMPOSITE EFFECTIVENESS

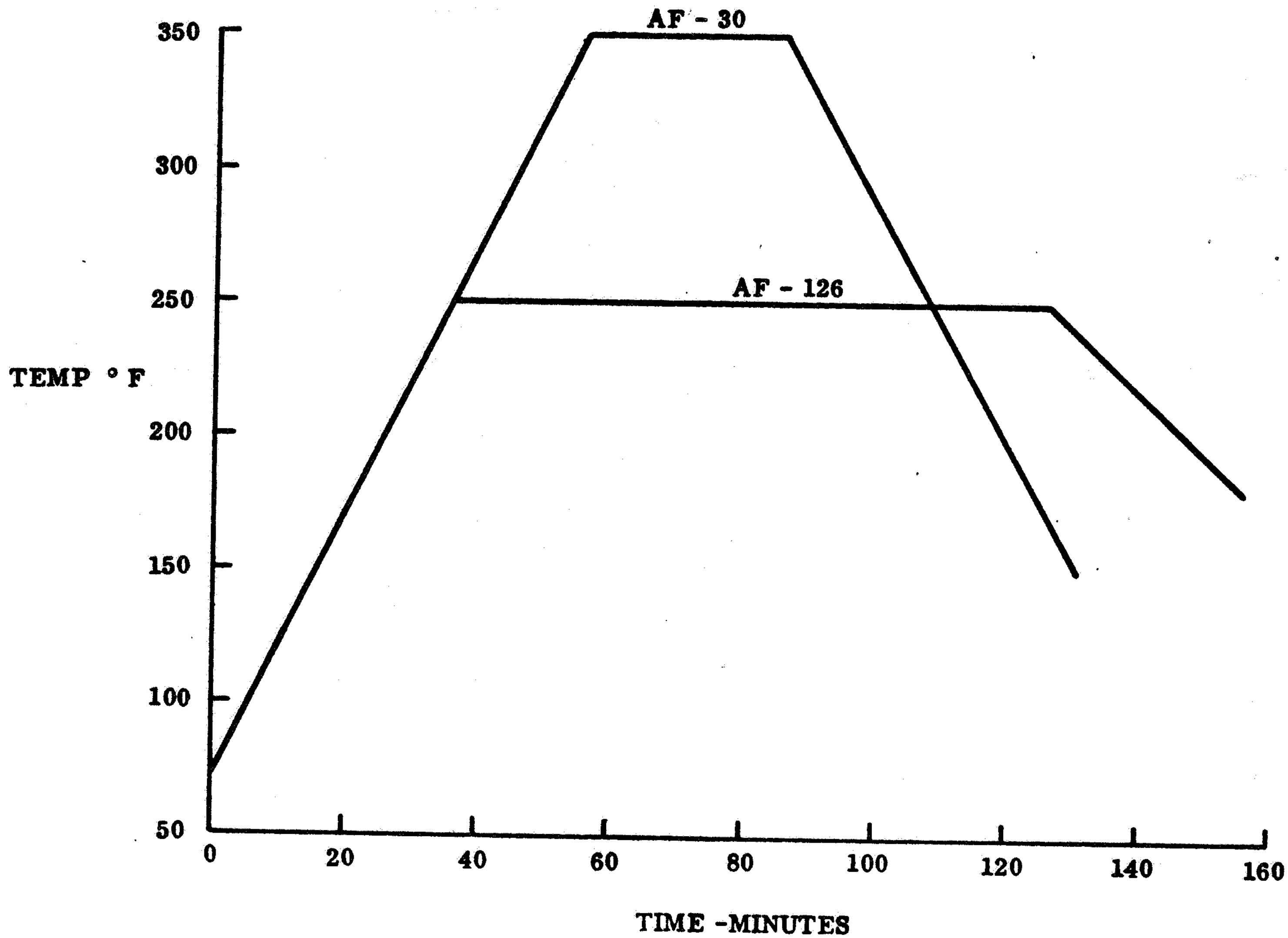

FIGURE 2 TYPICAL ADHESIVE CURE CYCLES

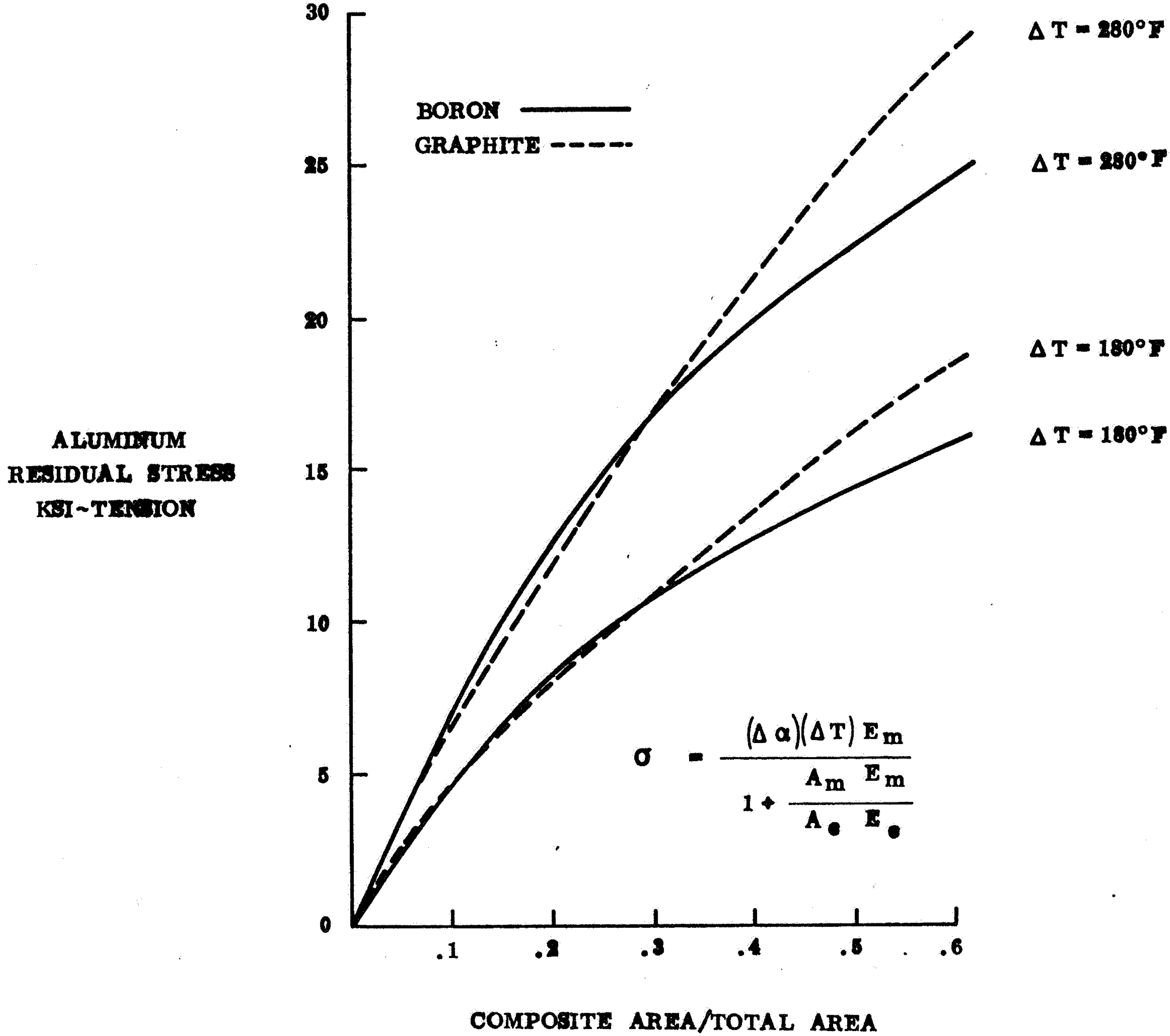

FIGURE 3 RESIDUAL STRESS WITH NO ALLEVIATION

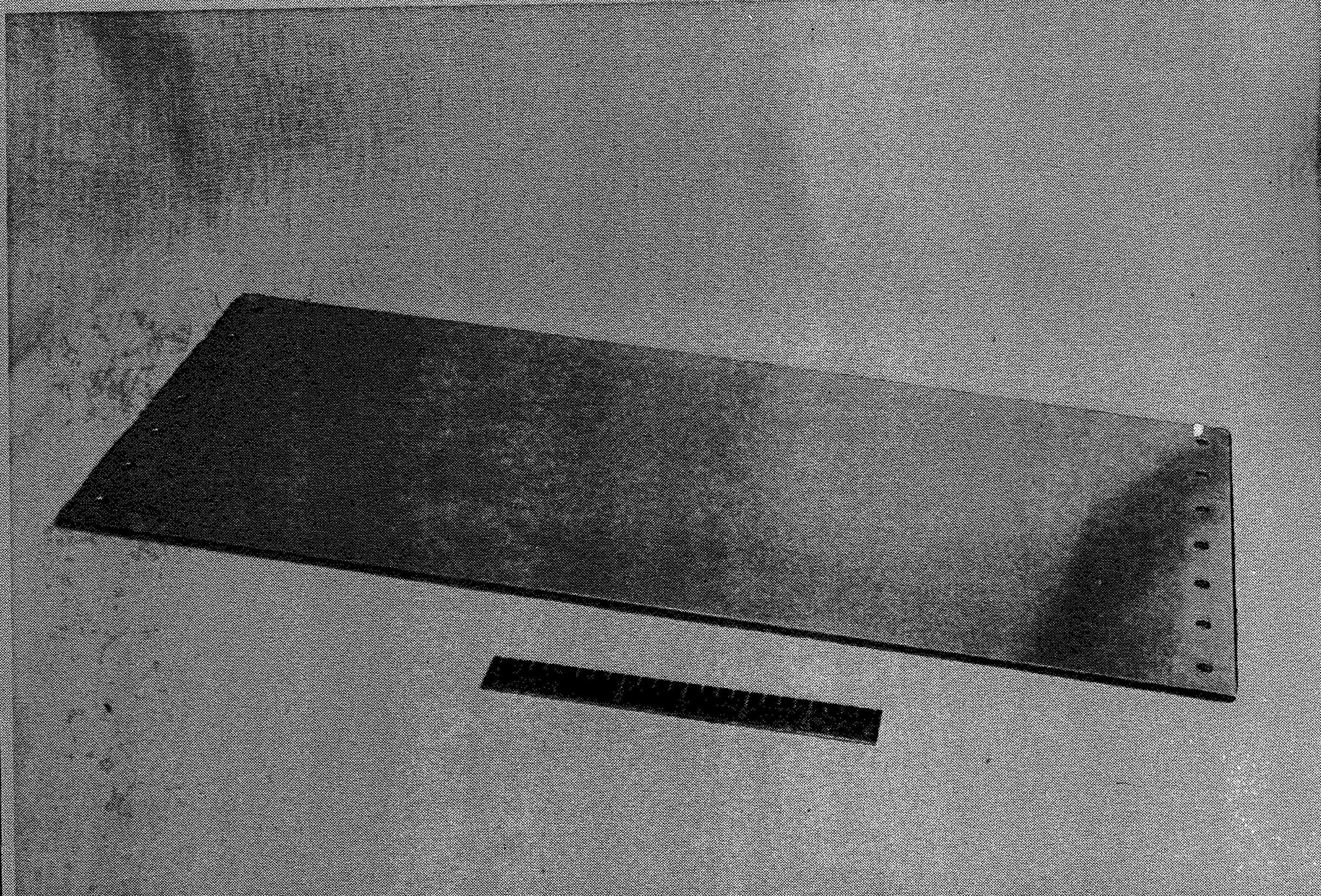

FIGURE 4 REINFORCED SHEET SPECIMEN

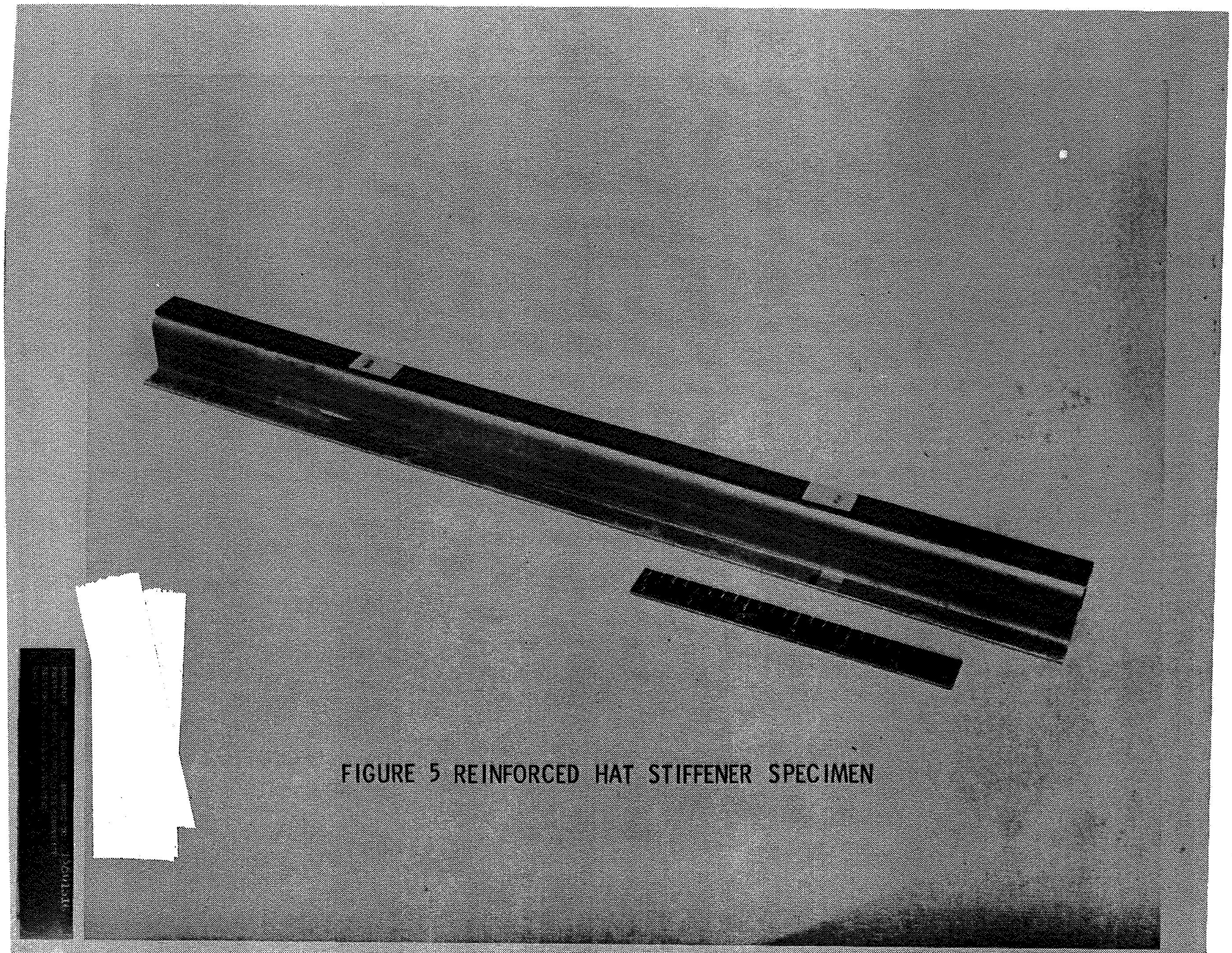

FIGURE 5 REINFORCED HAT STIFFENER SPECIMEN

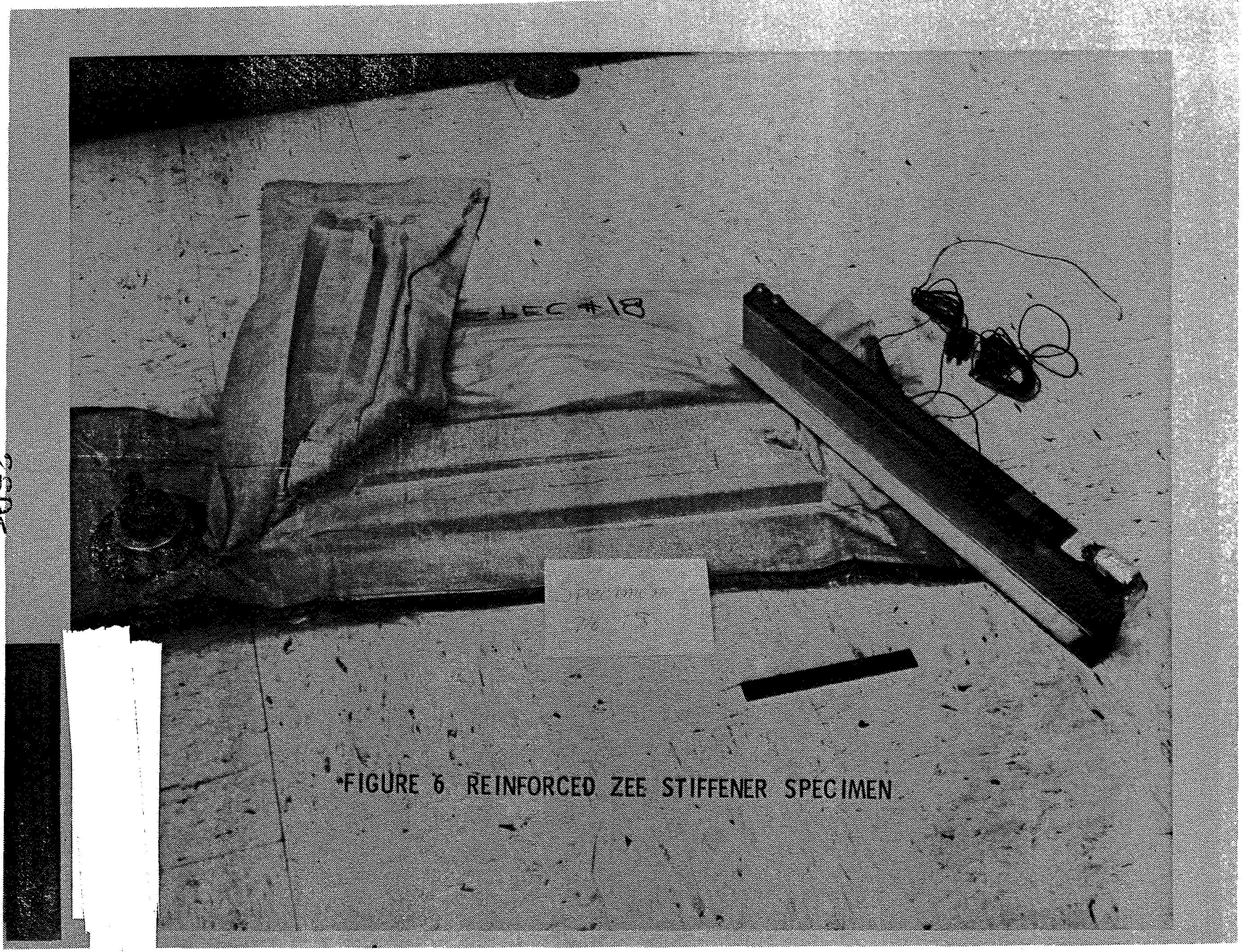

FIGURE 6 REINFORCED ZEE STIFFENER SPECIMEN

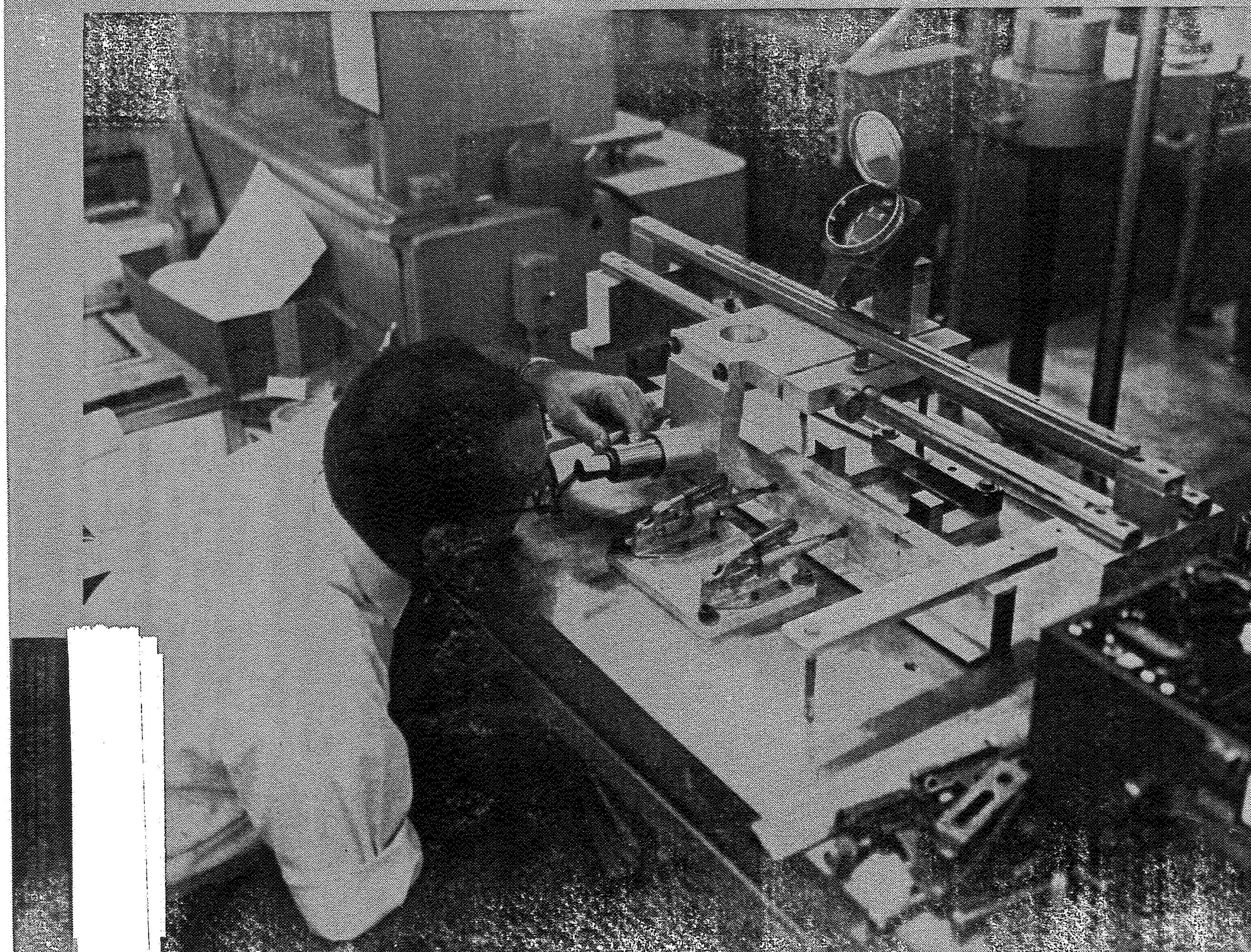

FIGURE 7 OPTICAL BENCH FOR LENGTH MEASUREMENTS

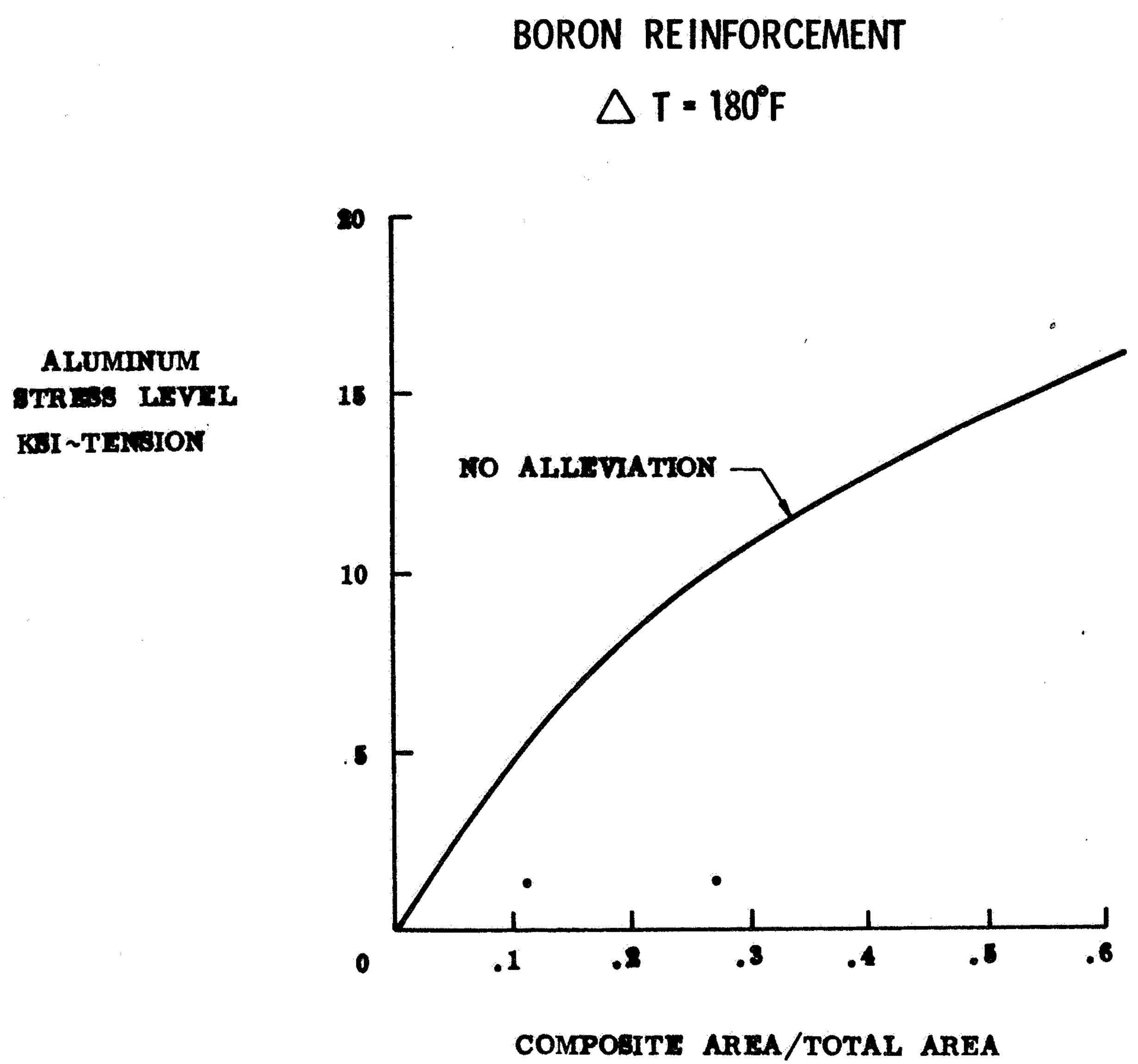

FIGURE 8 RESULTS - BORON REINFORCEMENT CURED AT 250°F

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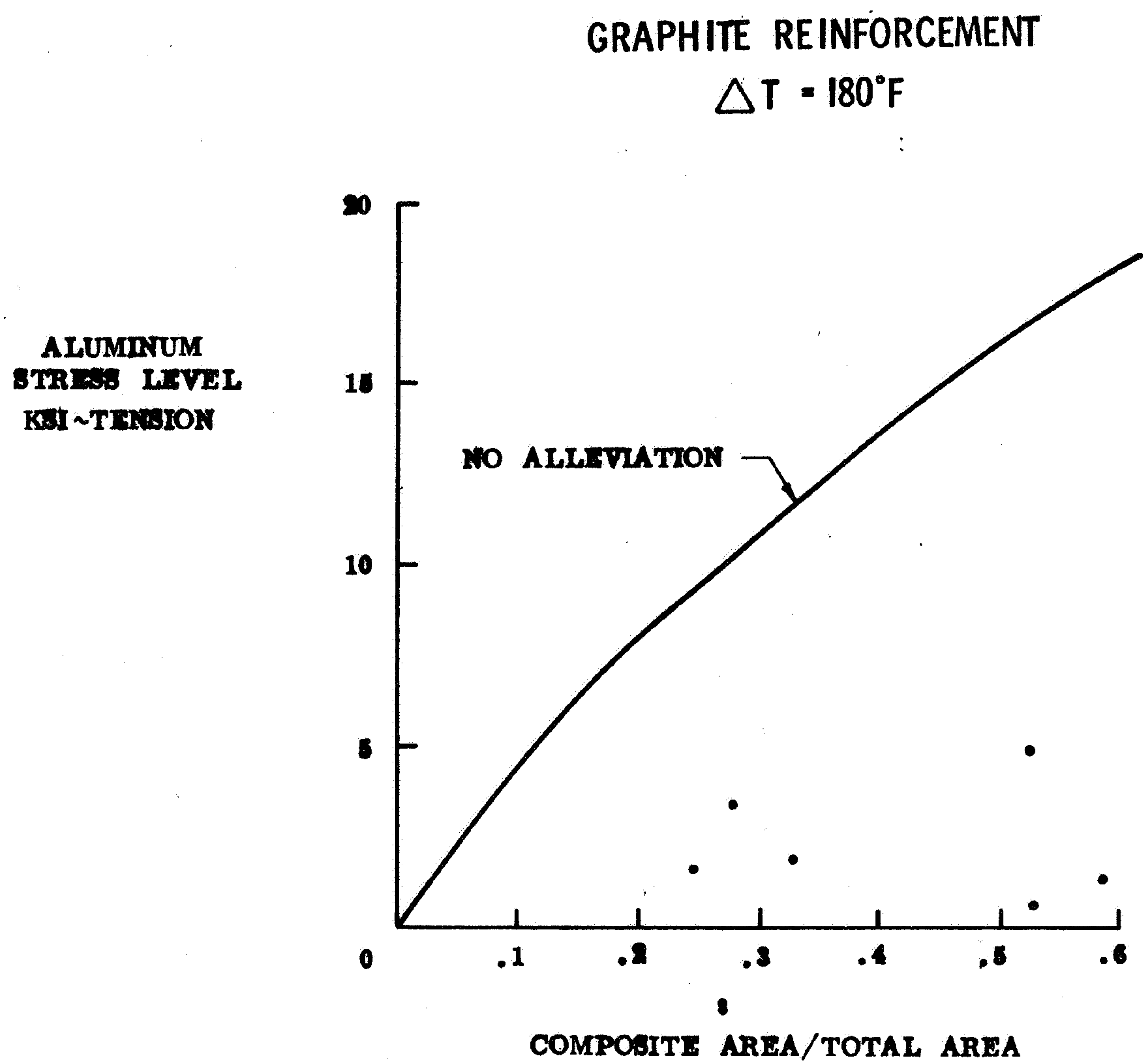

FIGURE 9 RESULTS - GRAPHITE REINFORCEMENT CURED AT 250 F

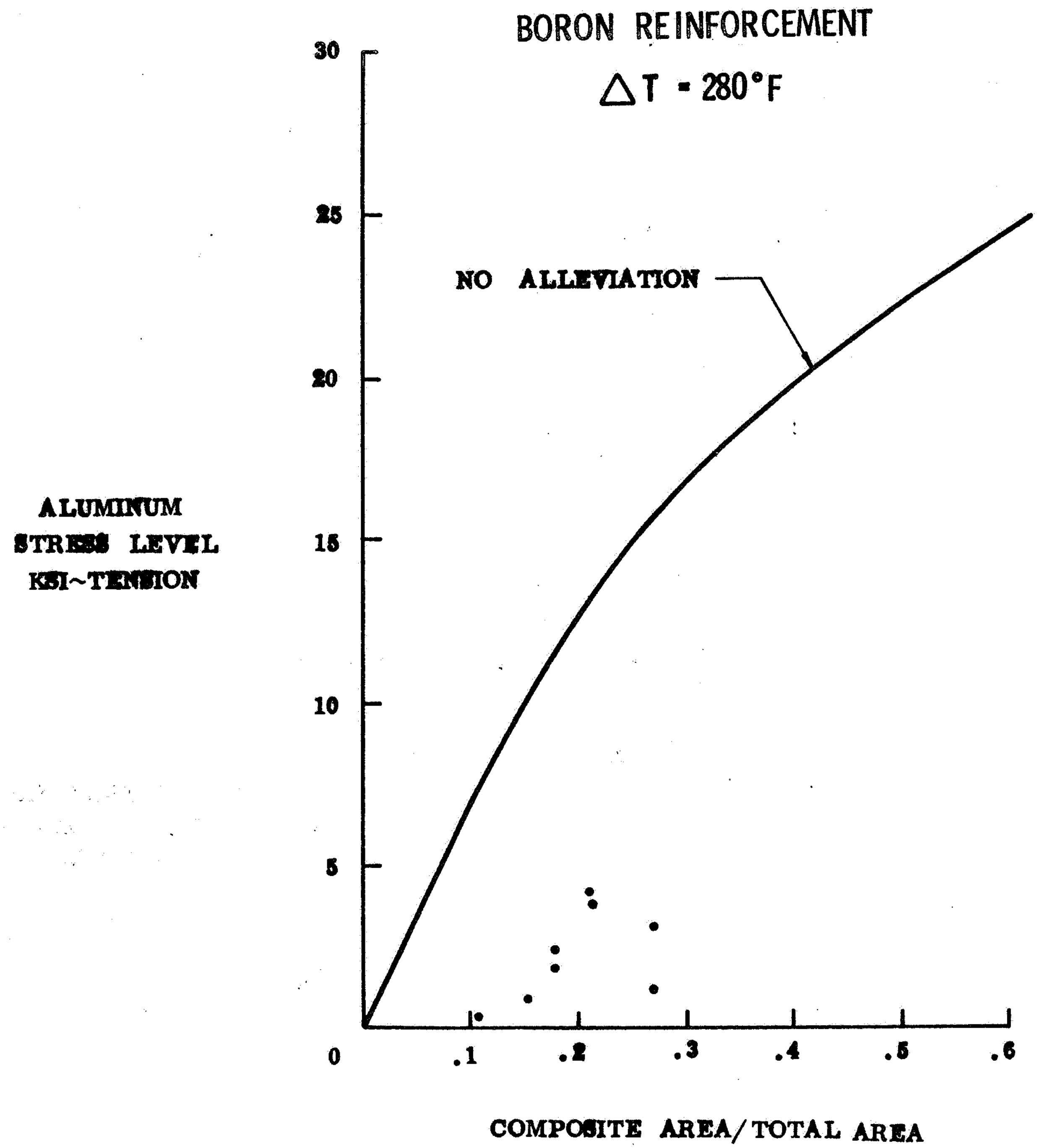

FIGURE 10 RESULTS - BORON REINFORCEMENT CURED AT 350°F

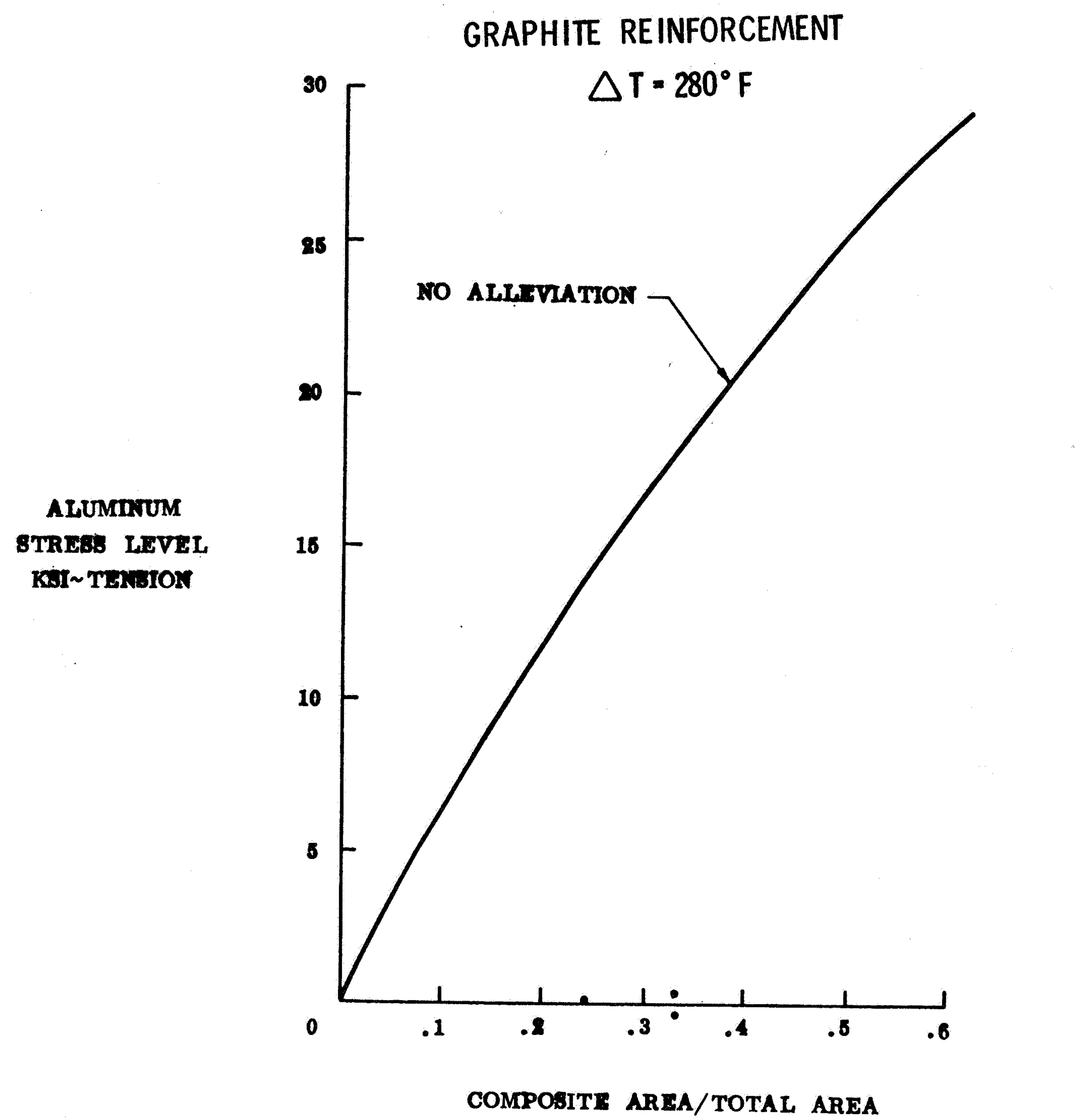

FIGURE 11 RESULTS - GRAPHITE REINFORCEMENT CURED AT 350° F

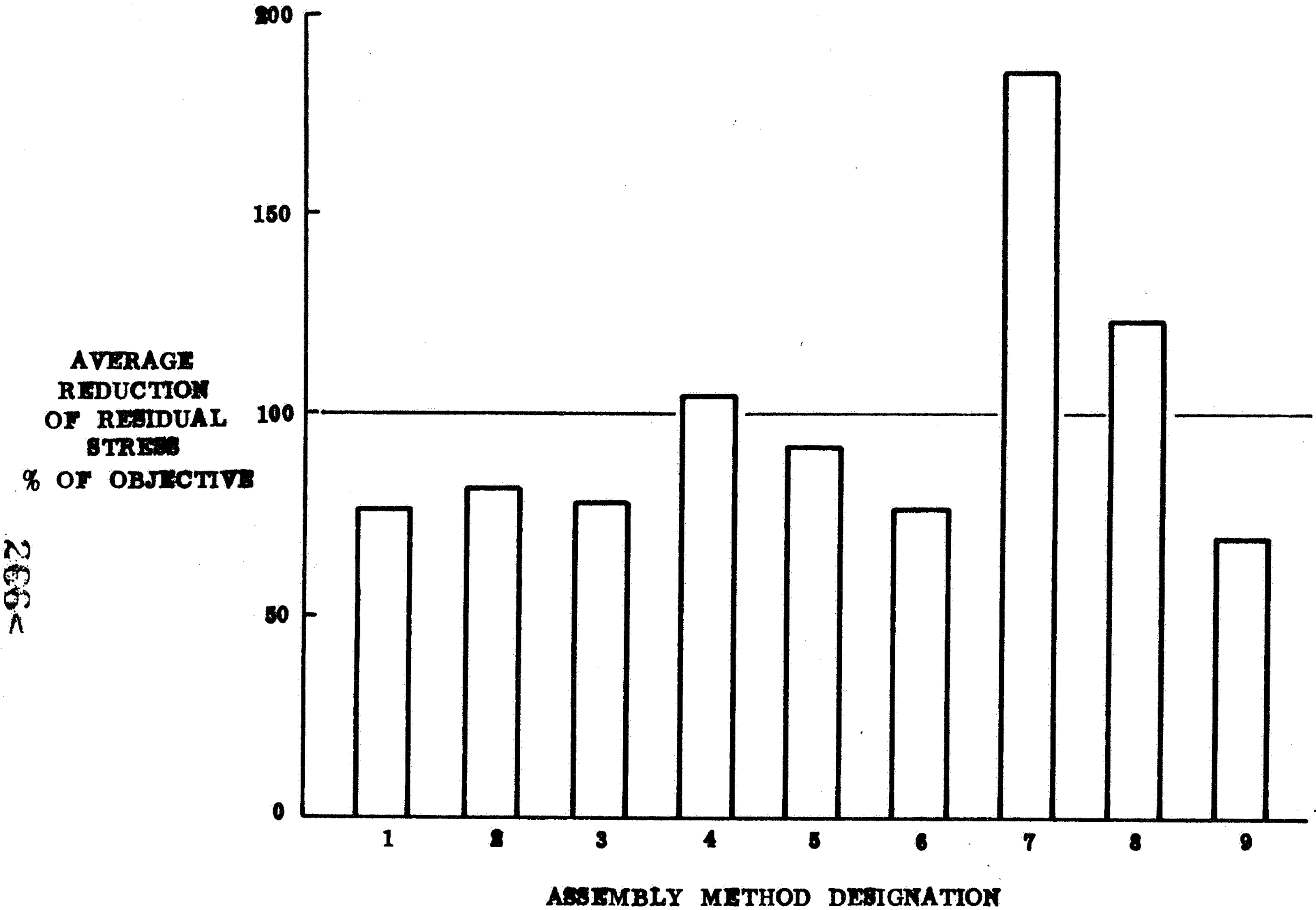

FIGURE 12 COMPARISON OF ASSEMBLY METHOD RESULTS

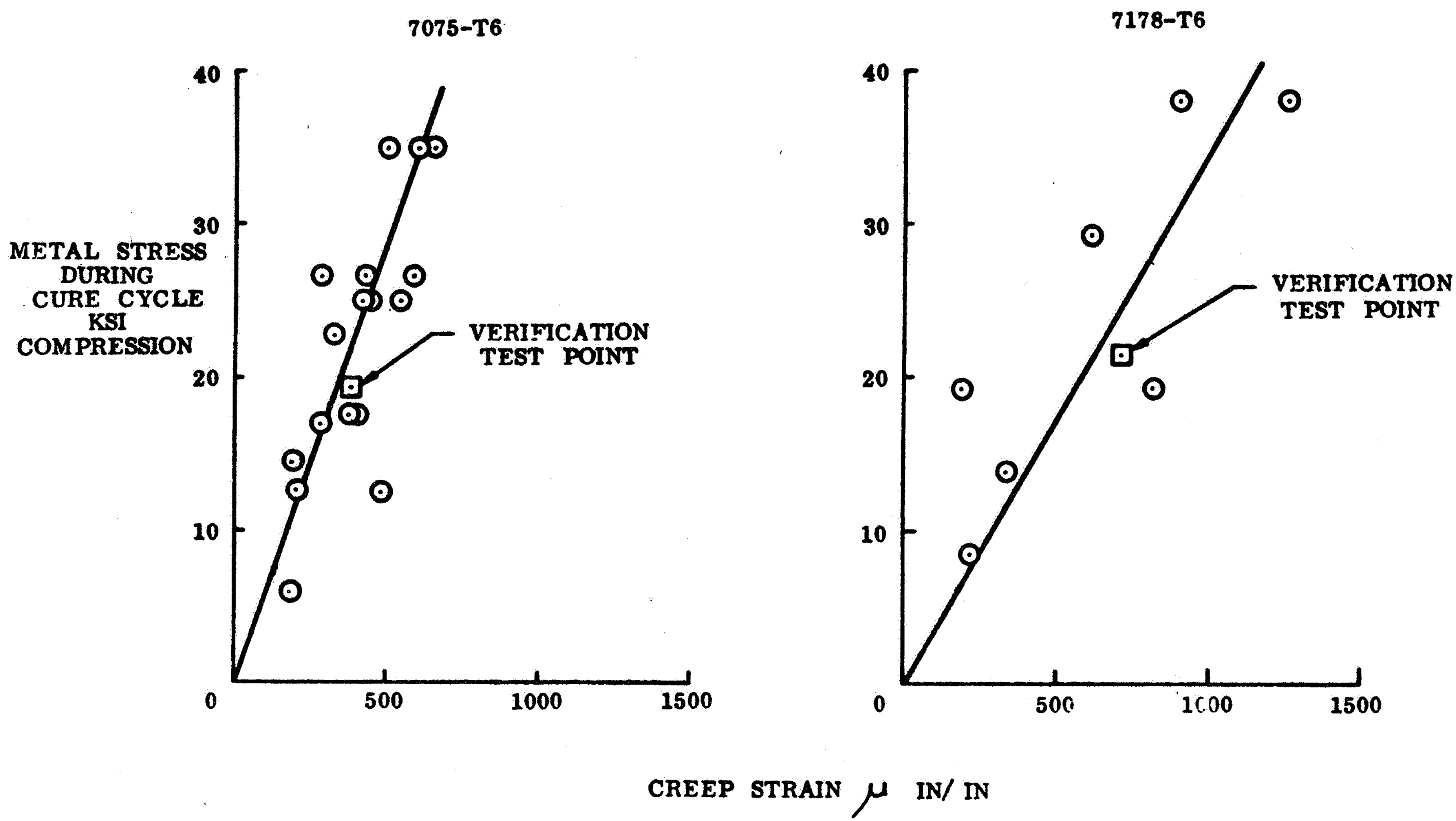

FIGURE 13 CREEP DEFORMATION OF ALUUMINUM