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Crazing and Degradation of Flexure Strength in Acrylic Plates as a Function of Time

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Based on our study, we conclude that for continuously stressed structural acrylic plastic components exposed to outdoor environment with 110°F maximum summer temperature, the maximum flexure design stress for a 10-year service life should not exceed 1000 psi; otherwise at the end of the service period, the remaining flexural strength of the weathered material will not provide the minimum required safety factor of 4.

We also recommend that stressed acrylic plastic structures only be cleaned safely with water-based cleaners.

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SUMMARY

Thick acrylic plates in stressed and unstressed condition have been subjected to outdoor weathering for 10 years. The stressed specimens developed surface crazing whose extent and depth were a function of flexure stress to which they were continuously subjected. Continuously applied flexure stress of 2240 psi generated very deep crazing, which resulted in catastrophic failure of the test specimen after 9 years. On the other hand, the specimen subjected to only 810-psi flexure stress displayed no crazing.

The effect of weathering on the strength of acrylic plastic varies with distance from the weathered surface. In *unstressed* specimens 0.040 inch below the weathered surface there is no measurable decrease in flexure strength, while on the surface there is approximately a 50-percent decrease. This decrease in strength on the surface of the specimen was not accompanied by crazing. For this reason, the absence of crazing cannot be considered absolute proof that the structural properties of acrylic plastic have not been reduced by weathering below the safe limits specified by American National Standards Institute/American Society of Mechanical Engineers (ANSI/ASME) PVHO-1 Safety Standard for Pressure Vessels for Human Occupancy.

Based on this study, we conclude that for *continuously* stressed structural acrylic plastic components exposed to outdoor environment with 110°F maximum summer temperature, the maximum flexure design stress for a 10-year service life should not exceed 1000 psi; otherwise at the end of the service period, the remaining flexural strength of the weathered material will not provide the minimum required safety factor of 4. This finding supports the design stress levels specified for acrylic plastic by ANSI/ASME PVH0-1.

Cleaning of stressed acrylic plastic structural components with organic solvents (i.e., alcohol, acetone, tylene, methylethylketone, etc.) is to be avoided as their application may accelerate by many orders of magnitude the degradation of flexural strength and/or appearance of crazing, depending on the solvent used. Because of this phenomenon, only water-based cleaners can safely be used on acrylic plastic structures.

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FIGURES

FIGURES (continued)

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INTRODUCTION

For years, users and manufacturers of plastics have been aware of a phenomenon whereby glassy plastics develop what appears to be a multitude of cracks, which initiate at the surface of the material and grow perpendicularly to the direction of stress (figure 1).* These discontinuities are not always cracks, however, and have been called "crazes" because they resemble, somewhat, the cracks found in glass and ceramics, particularly the glazes on pottery. Because many structures and structural components of pressure vessels subjected to hydrostatic pressures are made from glassy plastics (i.e., polystyrene, polymethyl methacrylate, and polycarbonate), the problems of crazing have become an important consideration in viewing the reliability and longevity of structural parts manufactured from these materials.

A craze, by definition, is a lens-shaped damage zone containing induced microvoids within a highly oriented polymer chain.[1] Within the crazed zone, voids comprise 40 to 60 percent of the area's volume.[2] These voids allow an increase in material cross section without lateral contraction because the lateral contraction is prohibited, at least in thick specimens, by the elastic constraint of the surrounding or adjacent undeformed polymer.[2]

The craze propagates transversely to the principal stress vector, thereby maximizing the spreading stress at the tip of the craze.[3] Crazes contain material which has a lower refractive index and density than the bulk of the resin.[4] They are characterized as being quite narrow and are often difficult to see. In laminated transparencies, premature crazing is a particularly serious problem because the crazes tend to form on the outer surface of the acrylic ply.

But what causes crazing? Studies have shown that there are at least four factors which may cause glassy plastics to craze: (1) tensile stress, (2) temperature differential across thickness of acrylic member, (3) weathering, and (4) contact with organic solvents. Crazes are initiated and propagated only when the tensile stress on the material surface exceeds some critical value. This critical stress value changes, however, as a function of ambient temperature and humidity, duration of stress loading, duration and intensity of solar or x-ray, irradiation, and duration of contact with organic solvents.[2,4]

Test results indicate that crazing will initiate when a specimen is exposed briefly to a stress level of approximately one-third of the failure stress,[5] and that the crazing will spread as the load duration increases.[6] However, crazing is also time dependent, and molded components may craze, with time, even when the magnitude of molded-in-strains are quite low.[7] In a comparison between polystyrene and acrylic, it was found that polystyrene is intrinsically stronger, but because polystyrene has a greater tendency to craze than acrylic, the observed ultimate strength of normal uncracked samples of acrylic was higher.[4]

In the case of crazing caused by weathering, casual observation of everyday glassy plastics shows innumerable examples of such crazing. However, the tests performed show that weathering, itself, is a surface effect and that the removal of weather-caused crazes returns the material to its approximate former state chemically and mechanically. However, if the material has been thoroughly exposed to high temperature (i.e., used in solar collector covers), or X-ray radiation (i.e., hyperbaric chamber viewports) degradation does occur through the hull thickness of the plastic.[8] Therefore, in such cases it is temperature and X-ray radiation that cause the material to degrade and not weathering, as such.

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*All figures and tables are placed at the end of the text.

Chemically induced crazing has been observed for many years. Most users of glassy plastics know they must not use organic solvents to clean the materials, particularly if they contain residual stresses or are subjected to tensile or flexure loadings (figure 2). Cleaners and disinfectants in a water solution attack acrylic, for example, less than the same cleaners and disinfectants in an alcohol solution.[9] Water, itself, even seawater immersion for as long as 5 years, does not cause any significant chemical change in acrylic.[10] Absorbed moisture gradient, however, can cause crazing as it generates a high surface tensile stress when the surface of a specimen has a high moisture content and is rapidly dried.[2] It is the stress, then, that causes the crazing and not the moisture, per se.

Even though most crazes are not true cracks, crazes are still believed to initiate failure of a structure or of a structural member when the crazing becomes extensive and the depth of crazing exceeds some critical value. In the critical flaw theories, it is assumed that the strength of a brittle material is limited by the presence of flaws in the sample, as these discontinuities distort the stress field and cause the initiation of the failure process by rapid extension of the largest, properly oriented flaw when a critical tensile stress is attained.[11]

Any one of the factors which cause crazing may be acting at any one time; however, usually more than one factor is present. There are probably synergistic effects between these factors. Little research with quantitative findings has been done on the magnitude of synergistic effects. The present study was conceived in an attempt to shed some light on major questions concerning the relationship between crazing, weathering, long-term application of flexure stresses, and structural performance of acrylic plastic structures made from thick plates.

The questions under investigation were as follows:

1. Does weathering decrease the flexure strength of thick acrylic plastic plates even without the presence of crazing?

2. Is the presence of sustained flexure stress required to initiate, maintain, and expand crazing in thick acrylic plastic plates exposed to weathering?

3. Does crazing significantly decrease the load carrying ability of thick acrylic plates loaded in tension or flexure?

4. Does sustained flexure stress accelerate the decrease of flexure strength in thick acrylic plates exposed to weathering?

5. Does the use of cleaners and disinfectants significantly accelerate formation of crazing on acrylic plastic under sustained tensile stress?

6. Is the absence of crazing a reliable indication that the acrylic plastic has not been affected by weathering?

The data generated by this study will be augmented to findings of other studies [12,13,14,15] which focused primarily on deterioration of tensile, compressive, and shear strengths due to weathering and immersion in seawater. The data generated by testing of coupons cut from the weathered 2.5-inch-thick spherical acrylic hull of submersible NEMO[15] is of particular interest as the hull was subjected during its lifetime primarily only to compressive stresses that have shown to have no effect upon material deterioration rate (tables 5, 6, 7).

EXPERIMENTAL APPROACH

To provide answers to the above questions, the test program was divided into three phases.

PHASE 1

In this phase of the test program, emphasis was placed on weathering of unstressed acrylic blocks for 10 years. The blocks were cut from 2- and 4-inch-thick Plexiglas G (table 1). From data provided in previous studies, it was known that hot, tropical climates tend to have the most effect in lowering the strength of their acrylic samples.[12,13,&14] Therefore, one set of specimens was placed at the Harbor Branch Oceanographic Institution in Linkport, Florida. Also airborne pollutants were suspected as possible sources of crazing in weathering samples, so some blocks were placed in Houston, Texas, at the Hahn and Clay facilities where they were exposed to a high level of hydrocarbon pollution. The third set of specimens was placed in El Cajon, California, in a hot, dry environment with more than 300 days per year of direct sunlight (figure 3). All of the blocks used in this phase of the study were plates with 12- by 12- by 4-inch and 12- by 12- by 2-inch dimensions. These samples differ radically from all previous weathered samples in that these samples were on an order of magnitude thicker (i.e., 4 or 2 inches versus .025 inch). If weathering is truly only a surface effect, thick specimens would exhibit this effect. None of the plate specimens were subjected to loading during the years they were exposed to the various environments. The specimens were placed in metal frames that kept them about 6 inches above the surfaces on which they were placed. The same face of the specimen was always facing towards the sun. Test coupons were periodically cut from weathered plates and tested for flexural strength (table 2).

PHASE 2

In this phase of the test program, 2- by 22- by 0.25-inch-thick strips of Plexiglas G were subjected to both stress and chemical solvents a combination which causes rapid crazing that culminates in failure. While under a constant 2000-psi flexure stress, various organic solvents were applied to the area of maximum stress on the acrylic strips, resulting in rapid crazing (figure 4). By holding the stress level constant, the effects of different chemon initiation and progress of crazing could be observed. The 2000-psi flexure stress was selected as the test stress level because this magnitude of stress is the industry-wide accepted standard for detecting the onset of chemically induced crazing.

Some of the test specimens were immersed in organic solvents and dried off prior to placing them in the test fixture and applying the bending moment for generation of 2000-psi flexure stress. This was done to determine whether contact with organic solvents prior to stress application sensitized the acrylic plastic to craze initiation as severely as contact with the same organic solvents during stress application.

Data that were generated in this phase of testing were (1) the time to initiation of crazing on the surface of specimen, (2) the depth of the crazing, and (3) the time to catastrophic failure of the flexure specimen.[9]

PHASE 3

In this phase of test program, six acrylic beams of 48- by 4- by 2-inch dimensions were mounted in an outdoor bending load fixture and subjected to six different stress levels. Seven beams were cut from a single sheet of 2-inch-thick Plexiglas G plate (figure 5). They were sawed, sanded, and polished at the edges. Approximately 2 inches from each end, 3 4-inch diameter holes were drilled without any visible cracks in the material. After all the machining drilling and polishing was accomplished, the beams were annealed at 190°F for 24 hours. Material coupons were also machined at this time from the top, middle, and bottom of the Plexiglas G plate to determine whether there was a significant difference in the mechanical properties of the material at these locations prior to outdoor weathering.

One end of each beam was attached to the mounting plate set in concrete by a threaded rod through the hole in the beam, and a steel nut was screwed down tightly on the beam (figure 6). A threaded eye bolt was then attached to the other end of the cantilever beam. After securing the eye bolt to the beam, a specified weight was suspended from the eye bolt by a wire placing the beam under a continuous sustained flexure stress loading (figure 7). A control beam was placed beside this test fixture on the rock outcrop. This beam was allowed to weather unstressed. All the beams were installed in the test fixture on 25 June 1977 at the test site in El Cajon (figure 8). Deflection readings were taken frequently to determine the rate of creep in test beams under different levels of sustained flexure stress (figure 9). The test was terminated on 31 January 1988 by removing weights from all the six test beams and recording the snap-back of the bent test beams (table 3).

After 24 hours of relaxation, the six test beams were loaded individually until fracture occurred. Maximum deflection and load at moment of failure were recorded (table 4). For comparison purposes an identical test beam No. 7 that was exposed to 10 years of weathering but not sustained flexure loading, was also mounted in the outdoor bending load fixture and was loaded to failure. The maximum load and deflection at failure were also recorded (table 4).

OBJECTIVES

PHASE 1

Deter...ne the effect of climate on the weathering of thick, unstressed acrylic plates.

Determine whether the change in material properties due to weathering is only a surface effect, or whether it extends through the whole thickness of acrylic plates.

Determine whether in unstressed acrylic plates a significant change in material properties is always accompanied by crazing of surfaces.

PHASE 2

Determine whether conta ' with organic solvents degrades the structural properties of acrylic plastic as much in unstressed specimens as it does in stressed specimens.

Determine the synergistic effect of sustained flexure stress on static fatigue of acrylic plastic in contact with organic solvents.

Determine whether contact with organic solvents generates crazing in unstressed acrylic specime..s.

Determine whether prior contact by unstressed acrylic with an organic solvent will initiate rapid crazing in the material after application of sustained flexure stress.

PHASE 3

Determine the relationship between the magnitude of sustained flexure stress and the rate of crazing on surfaces of acrylic plastic subjected to weathering.

Determine whether the reduction in flexure strength of weathered acrylic plastic specimens under long-term flexure loading is solely a function of weathering, or also of sustained stress level.

Determine the magnitude of *maximum* flexure stress that can be continuously applied to an acrylic structural component in an outdoor environment with a 110°F peak daytime temperature without the occurrence of catastrophic failure in less than 10 years.

Determine the magnitude of *maximum* flexure stress that can be continuously applied to an acrylic structural component in an outdoor environment with a 110°F peak daytime temperature without the appearance of crazing in less than 10 years.

TEST OBSERVATIONS

PHASE 1

There was no visible crazing on the surfaces of unstressed test plates subjected to outdoor weathering in El Cajon, Linkport, or Houston. There was observed, however, a dulling of surfaces that reduced the light transmittance in the visible spectrum by 10 percent. Weathering affects the physical properties of acrylic plastic only in a thin layer below the surfaces of the specimen, as shown by the large difference in tensile strength and molecular weight of coupons sliced both from the surface and either of the test plates (table 2).

PHASE 2

Wetting with organic solvents of surfaces on acrylic strips subjected to sustained flexure stress of 2,000 psi rapidly initiated crazing. Some solvents (i.e., benzene, xylene, aceton, and methylethylketone) initiated crazing instantaneously, while others (i.e., methyl, ethyl, and isopopyl alcohols) required several minutes to initiate crazing (figure 10). Prolonged exposure ultimately produced catastrophic failure of the flexure specimen due to transformation of the crazing into deep cracks.

Reducing the flexure stress level in the flexure specimens prior to wetting them with organic solvents increases the time required for initiation of crazing. While at sustained flexure stress of 2,000 psi, it required approximately 20 minutes for development of *severe crazing* while wetted by ethyl alcohol, at 1,000 psi the time interval increased to 200 minutes, and at 500 psi it was in excess of 1000 minutes. Thus, it appears that crazing will take place *at any stress level*, providing that wetting with the solvent is *continued indefinitely*.

Wetting followed by drying off of surfaces on unstressed specimens that were subsequently subjected to 2,000-psi flexure stress did not appear to have the same effect as wetting of stressed specimens. While wetting with ethyl alcohol of specimens under sustained 2,000-psi flexure stress *initiated crazing* in approximately 1 minute and resulted in catastrophic failure in about 30 minutes, wetting and drying of unstressed specimens followed by application of 2,000-psi flexure stress did not initiate crazing even after 1,000 minutes of sustained loading.

PHASE 3

Test beams *did not craze significantly* even after 10 years of weathering if the maximum tensile flexure stress on the beam's surface was less than 810 psi. In the highly stressed beam No. 1 crazing became very noticeable in one year, in beam No. 2 after 2 years, and in beam No. 3 after 4 years, and in beam No. 4 only after 5 years (figures 11 through 17). Whenever present, the crazing was limited to a small area on the top surface above the cantilever beam fulcrum, where the tensile flexure stress was the highest. The extent and depth of crazing decreased rapidly with distance from the beam fulcrum until, at some distance, it disappeared totally. In beam No. 1, the crazing was observed only within 6 inches of the fulcrum. In that beam, the stress level at 6 inches from the fulcrum was calculated to be 1900 psi.

The catastrophic failure of the test beam No. 1, subjected to 2,240-psi sustained flexure stress for 9 years, indicates that all test beams under sustained loading will ultimately fail; the duration of loading required for failure will vary, however, inversely with the magnitude of sustained stress level (figure 18).

Application of sustained flexure stress to acrylic plastic can have a larger effect on its effective (residual) flexural strength than weathering; however, there is no doubt weathering significantly accelerates the effect of static fatigue (table 4). For example, test beam No. 7, which was subjected to weathering but not to sustained flexure stress for 10 years, had an effective flexural strength of 9,300 psi (i.e., lost 45 percent of original strengths) while beam No. 1, which in addition to weathering was also subjected to sustained flexure stress of 2,240 psi, lost 100 percent of its effective strength after 9 years (i.e., it failed). At low sustained stress levels, the effect of weathering exceeds the effect of static fatigue on effective strength. For example, beam No. 6 subjected to a sustained low stress level of 810 lost 45 percent of its original strength due to weathering and only 25 percent due to static fatigue. After 10 years of weathering, the crazing was *very severe* on test beams No. 1 and 2 (figures 19 and 20), *moderately severe* on test beam No. 3 (figure 21), *barely noticeable* on test beams Nos. 4 and 5 (figures 22 and 23), *incipient* on test beam No. 6 (figure 24), and *totally absent* on unstressed test beam No. 7 (figure 25). The extent and depth of crazing did not increase during the short-term flexure test to destruction conducted at the conclusion of the 10-year-long sustained flexure loading test program (figure 26).

The deflections of the test beams after 10 years of sustained flexure loading were proportional to the magnitude of flexure loading to which they were subjected (figure 27). Most of the deflection took place within 1 day after application of sustained flexure loading; the rate of creep decreased significantly thereafter.

The deflection of test beam No. 1 at catastrophic failure after 9 years of sustained flexure loading (figure 27) was significantly less than of test beam No. 7 during short-term destructive testing (figure 28). This was also true of test beams Nos. 2, 3, 4, 5, and 6 (tables 3 and 4).

The effective strength of test beams 2, 3, 4, 5, and 6 was, after 10 years of sustained flexure loading, found to *be significantly less* than that of test beam No. 7 not subjected to sustained flexure loading (figure 3).

DISCUSSION

EFFECT OF WEATHERING

The data generated in this study, as well as in previous studies conducted by the authors[15] on the effect of weathering on the physical properties of acrylic plastic with ultraviolet absorber, very strongly support the following findings:

1. *Weathering degrades the physical properties* of acrylic plastic. The molecular weight and flexural strength decreases, while the material becomes more brittle (tables 2, 4, 5, 6, and 7).

2. *The effect of weathering does not penetrate deeply below the surface*; 0.06 inch below the surface the physical properties of the material remain unchanged (table 5).

3. *The physical properties most affected by weathering are the flexure strength, tensile strength, and tensile elongation at failure.* Shear strength is affected very little and the compressive strength almost none at all (table 7).

The flexure strength is the most affected by weathering because during bending the highest tensile component of the flexure stress is generated at the surface of the material where the effect of weathering is the greatest. The cracks, which originate during flexure loading in the weak, brittle surface layer, penetrate readily into the body of the unweathered material causing it to fail catastrophically.

The scenarios are quite different for acrylic plastic specimens under tensile or shear loading, where the stresses are uniformly distributed across the thickness of the specimen. Because of the uniform stress distribution across the thickness of the material, the layers of degraded material contribute very little to the overall reduction of strength in the 0.25-inch-thick test coupons. In structural components several inches thick, the effect of a weathered surface layer on the performance of the components loaded in tension is not significant.

Compressive strength of acrylic plastic structural components is totally unaffected by weathering as the stresses are uniformly distributed across the thickness of the components and, furthermore, the compressive strains prevent the initiation of cracks in the external weathered surfaces.

Based on the above discussion, we can postulate that *thick* structural members subjected to bending movements (for example, plane windows in pressure chambers) are as much affected by weathering as *thin* components, since the maximum tensile strain generated by flexure stress is always located on the surfaces most affected by weathering. For this reason, *the structural performance of new thick plane windows must be discounted for future deterioration due to weathering by the same percentage as the structural performance of new thin plane windows.*

Thus for a projected operational life of 10 years, the original flexure strength of acrylic plastic materials used in a structure must be discounted by *at least 35* and preferably *50 percent*. If the structure is subjected for 10 years to the maximum sustained flexure stress recommended by ANSI ASME PVHO[16] for a 125°F peak temperature, the static fatigue further reduces the effective flexure strength, so the original flexural strength must be discounted instead by *75 percent*. Data are not available for prediction of flexural strength in acrylic plastic that in addition to weathering is also subjected to cyclic flexure loading; for example, frequently pressurized plane windows in pressure chambers. A conservative assumption can be made, however, that weathering and cyclic application of flexure stresses *does not* decrease the flexural strength more than a sustained application of the same flexure stress.

Since the compressive strength of a structural member is not affected significantly by weathering (less than 2 percent) the structural performance of acrylic plastic structures loaded in compression need not be discounted for the effects of weathering, as is the case for structures subjected to flexure loading (table 7). Because of this observation it is desirable that, whenever feasible, acrylic plastic structures be designed for compressive, rather than flexure or tensile, loads. Thus, it is always preferable that viewports be curved rather than plane, even though the fabrication process for curved viewports is more expensive than for plane ones.

The effect of weathering on the tensile strength of acrylic plastic structures is significantly less than on the flexure strength, mostly because the tensile stress in a structural member under pure tension is distributed evenly across its thickness. This holds also true for the 0.25-inch-thick test specimens used for the determination of tensile strength in weathered thick plates. If the thickness of the tensile test specimens could be somehow reduced to 0.020 inch, the tensile strength of the weathered acrylic would be found to be the same as the flexure strength determined by 0.25-inch-thick flexure test specimens cut from the thick weathered plates.

Since this study did not address testing for tensile strength, data will be used from previous studies[15] to determine by how much the tensile strength should be discounted for the effect of weathering. Data from previous studies show that the tensile strength of acrylic plastic members of a structure can be expected to decrease after 10 years of weathering by approximately 20 percent (table 7). Thus, it appears that tensile loading is less desirable than compressive loading, but certainly more desirable than flexure loading.

The shear strength appears to be even less affected by weathering than tensile strength (table 7). This is probably due to the fact that the test specimens for testing of shear strength are 0.5 inch thick and the distribution of shear stress across the specimen is fairly uniform. The reduction of strength due to weathering based on data from previous studies appears to be about 10 percent. Thus weathering affects the shear strength of acrylic plastic, as determined by standard test specimens, less than the flexure or tensile strength.

EFFECTS OF STRESS

Since most acrylic plastic structures or structural components subjected to weathering are also stressed either continuously or intermittently, the effect of stress on the effective strength of acrylic plastic must also be considered. As continuously applied stress is known from the published literature to affect the strength of an acrylic structure more than infrequent stress application, it was chosen for this study. The type of loading selected was flexure loading, as it would affect the flexural strength of materials shown to be the most sensitive to effects of weathering.

The range of stresses to which the flexure test beams were subjected was rather wide; the highest stress level chosen (2,240 psi) was to produce catastrophic failure in less than 10 years, while the lowest stress (810 psi) was not to initiate any significant crazing in 10 years. The test results confirmed this; test beam No. 1 under sustained flexure stress of 2,240 psi failed catastrophically after 9 years, while test beam No. 6 under sustained flexure loading of 810 psi did not exhibit any significant crazing.

The catastrophic failure of test beam No. 1 and the effective strengths of test beam Nos. 2 through 6 at the end of the 10-year-long test program (table 3) that were lower than the original strength of the material (table 1) confirm the existence of static fatigue, which was well documented by other investigators in technical literature. What this study added to the already published body of data is the contribution that weathering makes to the reduction in original flexure strength of thick beams under sustained flexure loading.

The reduction in strength due to static fatigue *alone* can be estimated by comparing the effective strengths (as denoted by maximum flexure stress during short-term testing to failure) of weathered test beams subjected to sustained flexure loading (test beams Nos. 1, 2, 3, 4, 5, & 6) with the remaining strength of the test beam that was weathered, but not subjected to sustained flexure loading (test beam No. 7). In this particular case, the effect of weathering by itself reduced the original strength of test beam No. 7 from 17,000 to 9,300 psi or to approximately 55 percent of original strength (table 4).

The additional reduction in strength due to static fatigue of the material was very significant, and the magnitude of this reduction in strength varied with the level of sustained stress to which the test beam was subjected. The static fatigue together with 10 years of weathering reduced the effective strength of flexure test beams to the following percent of original strength:

Test beam No. 1 — 0 percent

Test beam No. 2 — 19 percent

Test beam No. 3 — 22 percent

Test beam No. 4 — 24 percent

Test beam No. 5 — 25 percent

Test beam No. 6 — 30 percent

Since weathering alone appears to have reduced the flexure strength to 55 percent of original strength, the contribution of static fatigue to reduction of strength can be estimated. It is estimated that fatigued flexure beams would have retained the following percent of original strength if the effects of weathering were discounted:

Test beam No. 1 — 45 percent

Test beam No. 2 — 64 percent

Test beam No. 3 — 67 percent

Test beam No. 4 — 69 percent

Test beam No. 5 — 70 percent

Test beam No. 6 — 74 percent

A brief inspection of the estimated strengths that would remain in the flexure test beams if, during the sustained flexure loading they were not exposed to weathering, leads us to the opinion that at sustained stress levels below 2,000 psi weathering contributes more to reduction of original strength than static fatigue by itself.

Since the study did not address itself to intermittent stress application, there are no data on which to form an opinion on the contribution of cyclic stress fatigue to the reduction of original strength in weathered structures. A conservative opinion, however, can be formulated which states that the reduction of materials strength in an acrylic structure subjected to both weathering and intermittent flexure stress does not exceed the reduction in strength measured on flexure test beams subjected to both weathering and continuous sustained loading.

DESIGN STRESS SELECTION

Since both weathering and application of flexure stress reduce the effective strength of acrylic plastic, the reduction in effective strength after 10 years of service must be taken into account in the selection of design stress for any acrylic plastic structure or structural components that are subjected to flexure loading (i.e., plane windows under pressure loading, horizontal panels, and beams under gravity loading, etc.). Obviously, the *lower the value of design stress* the *higher the effective safety factor*, and the *lower the extent of crazing* will be after 10 years of operational service in outdoor environment.

Economic considerations, on the other hand, dictate that the design stress should be as high as possible without undue increase in risk of catastrophic failure. The highest design stress level that meets both safety and economic considerations is based on the premise that at no time during the operational life of the acrylic plastic shall the *effective safety factor* decrease below the value of 2. Flexure test beam No. 3 met this criteria after 10 years of sustained flexure loading at the 1570-psi maximum stress level. It still could withstand a *short-term* flexure stress of 3,800-psi magnitude prior to failure during short-term destructive testing in 65°F ambient air environment. The maximum safe design stress experimentally validated by flexure test beam No. 3 also meets the maximum design stress criteria of ANSI/ASME PVHO-1 for maximum ambient air environment temperature in the 100 to 125°F range. The minimum conversion factor (short-term critical stress divided by long-term design stress) specified by ANSI/ASME PVHO-1 for the 100 to 125°F temperature range is 10, which is readily converted into minimum design stress range of 1400 to 1700 psi magnitude (the exact value depending on the short-term flexural strength of acrylic plastic used in the construction of the structure).

Although a design stress of approximately 1500 psi will provide a minimum safety factor of at least 2, even at the end of the 10-year life operational period, it will not prevent the appearance of crazing that detracts from the appearance of the acrylic structure after about 5 years in an outdoor environment. To prevent the appearance of crazing during the 10-year operational life period calls for a maximum design stress of less than 810 psi. Flexure test beam No. 6 stressed to this sustained stress level did develop only barely noticeable crazing during the 10-year test period in outdoor environment. This design stress level for avoidance of significant crazing during a 10-year operational life translates into a minimum conversion factor of approximately 20. At this design stress level, the minimum effective safety factor at the end of 10-year service period is calculated to be 6.

From this discussion, it appears that the minimum conversion factor of 10 specified by ANSI/ASME PVHO-1 represents from the safety viewpoint the *maximum acceptable value of design stress* for an acrylic pressure-resistant window with a 10-year operational life in an outdoor environment with peak temperatures in 100 to 125°F range. At this design stress level, there will be, however, very noticeable crazing that may prompt the replacement of the pressure resistant window in less than 10 years. It would appear, therefore, cost effective to select for large, expensive plane windows, as in underwater observatories, a lower design stress preferably in the 500- to 800-psi range (conversion factors 30 to 20) to insure absence of crazing for 10 years.

DEFLECTIONS

The deflection of the cantilever test beams followed the classical strain theory for acrylic plastic (table 4). The *instantaneous deflection* after hanging of the dead weight from the tip of the beam was large, and its magnitude could be predicted on the basis of classical theory for bending of cantilever beams fabricated from totally elastic isotropic material with modulus of elasticity in the 450,000- to 500,000-psi range. The deflection continued to increase rapidly during the first hour after load application; the rate of creep, however, immediately began to decrease exponentially and continued to do so at this rate for approximately 24 hours.

After 24 hours, the creep rate stabilized into a logarithmic relationship between time and strain. Because of this logarithmic creep rate, the magnitude of beam deflection could be predicted for any time in the future using a mathematical formula and two deflection measurements.

$$M = \frac{\log \dfrac{d_2}{d_1}}{\log(T_2 - T_1)}$$

where

M = slope constant for a straight line expressing effective modulus elasticity decay on log coordinates.

d_1 = deflection at time T

d_2 = deflection at time T_2

$T_1; T_2$ = time, usually 1 to 10 days (a later reading may be substantiated for the 10-day reading).

The 0.057 value of M was calculated on the basis of 3.04- and 3.50-inch displacements recorded 1 day and 13 days after load application to test beam No. 2. Using M = 0.057, the deflection of test beam No. 2 was predicted to increase to *4.83 inches* in 10 years; this value compares rather well with the measured deflection of *5.0 inches*. The calculated value of M compares also well with published value of M in technical literature for MIL-P-5425 polymethyl methacrylate in 70°F environment (figure 29). The good agreement between experimentally measured displacement after 10 years and the calculated displacement was not expected, as the ambient temperature during this time period fluctuated for 45 to 110°F. The only possible explanation for this good agreement between the experimental and calculated data is that during the first 13 days of load application, when deflection d and d_2 were measured for the determination of M, the ambient temperatures were in the upper half of the 45 to 110°F temperature range experienced during the following 10 years. This is a reasonable explanation, as during the typical year in El Cajon, the ambient temperature remains above 70° more than 70 percent of the time.

Also note that the deflections of the test beams after 10 years of sustained loading are approximately twice as large as instantaneous deflection upon load applications (table 2). Thus, a rule of thumb can be formulated which states that to predict the deflection of an acrylic structure after 10 years of sustained load application, measure the instantaneous deflection after application of the load and multiply it by a factor of 2.

FINDINGS

1. The effective flexural strength of acrylic plastic decreases with duration of exposure to outdoor weathering. After 10 years of weathering, the effective strength is only approximately 55 percent of original strength.

2. Sustained flexural stress decreases the effective strength further; at the 1500-psi maximum design stress level specified by ANSI/ASME PVHO for the peak ambient temperature range of 100 to 125°F, the total effective strength after 10 years of weathering is approximately only 3800 psi providing an effective safety factor of only 2.

3. The maximum design stress for avoidance of crazing during 10 years of sustained flexure loading and weathering appears to be <810 psi. Using the crazing avoidance design stress provides, at the end of 10-year-long service period, a strength of 30 percent and an effective safety factor of 6.

4. Weathering affects only the first 0.060 inch of thickness in acrylic plastic (MIL-P-5425); the remainder of the material retains its original strength even after 10 years of weathering.

5. The compressive strength of acrylic plastic structures appears not to be affected at all by weathering.

6. The deflection of acrylic structures during a 10-year-long period while under sustained flexure loading can be predicted on the basis of deflection measurements taken on the first and tenth day after the application of sustained loading.

7. The deflection after 10 years of sustained flexure loading appears to be 100 percent greater than the deflection immediately after application of sustained load.

8. Cleaning with organic solvents of acrylic plastic surfaces under tensile strain produced by flexure or tensile stresses accelerates the crazing process. Alcohol contained by most disinfectants and window cleaners will initiate crazing in several minutes on acrylic plastic surfaces that are under tensile stresses of 2000 psi and in several hours on surfaces that are under stresses of 1000 psi.

9. Cleaning with organic solvents prior to application of stress *does not* initiate crazing in realtime after load application.

10. Degradation of physical properties in acrylic plastic due to weathering appears to correlate well with the decrease of molecular weight in the material affected by weathering.

*These findings have been experimentally validated only for non-cross-linked polymethyl methacrylate plastic with ultraviolet filter additive meeting the requirements ANSI/ASME PVHO, section 2, table 2.1-1, and/or MIL-P-5425.

CONCLUSIONS

1. Weathering affects only a thin surface layer on acrylic plastic with ultraviolet absorber: the affected material becomes more brittle and less able to withstand tensile strains.

2. The effective load-carrying capacity of thick acrylic plastic structural members under flexure loading (i.e., pressure proof windows, beams, roof paneling, etc.) is determined by the reduced mechanical properties of the thin weathered surface layer subjected to peak flexure stresses.

3. The flexure design stress of 1500-psi magnitude (i.e., conversion factor of 10) specified by ANSI ASME PVHO-1 for plane pressure proof windows subjected to weathering and a biaxial tensile stress field in ambient environment with peak temperatures in the 100 to 125°F range provides an adequate effective safety factor of 2 at the end of the 10-year service period.

4. Crazing of acrylic structures subjected to weathering and sustained flexure loading can be avoided over a 10-year period by specifying maximum flexure design stress ≤800 psi (i.e., conversion factor ≥20).

5. Cleaning of acrylic surfaces under applied, or residual, tensile strain with organic solvents (alcohol, methylethylketone, trichloroethylene, benzene, etc.) will accelerate the formation of crazing by several orders of magnitude, leading in some cases to immediate catastrophic failure.

6. The experimental data are insufficient to allow prediction of effective strength in flexure loaded acrylic plastic structure after 20 years of weathering; it is certain, however, that the design stresses (i.e., conversion factors) specified by ANSI ASME - PVHO for windows under flexure loading will not provide an adequate effective safety factor after 10 years of sustained loading in an outdoor environment.

7. It is preferable to design acrylic plastic structural components for compression rather than flexure or tensile loading, as weathering and sustained loading do not decrease significantly the compressed strength of acrylic plastic even after 10 years of exposure.

8. The most sensitive analytical tool for detecting the effect of weathering on acrylic plastic and its depth of penetration into the material is the measurement of molecular weight performed on thin coupons of material sliced from the surface of weathered material.

9. The most feasible approach to eliminating the effect of weathering on the effective strength of acrylic plastic structural members under flexure loading is to de-couple the weathered layer from the body of the structural member, so that a crack initiated in the weathered layer does not propagate into the body of the material, causing it to fail catastrophically. This can be accomplished by laminating a thin sheet of acrylic plastic with elastomeric adhesive to the thick structural member; a crack originating in the weathered layer would not propagate across the elastomeric adhesive interlayer into the body of the structural member.

RECOMMENDATIONS

1. The 1500-psi maximum design stress value specified by ANSI/ASME PVHO-1 (i.e., conversion factor of 10) for plane windows in chambers for human occupancy operating in ambient environment with peak temperatures in the 100 to 125°F range should not, for any reason, be increased to a higher value, as this will decrease the effective safety factor of the window after 10 years of service to less than 2.

2. To eliminate the appearance of unsightly crazing for a period of 10 years on the weathered surfaces of plane acrylic plastic windows in chambers for human occupancy, the design stress should not exceed 800 psi (i.e., conversion factor of 20).

3. Installed acrylic plastic windows should not be cleaned with anything but water and mild detergents approved for washing of dishes.

4. Brand new acrylic plastic windows of any shape (plane, spherical, and cylindrical) should, prior to installation in chamber viewports, be inspected under polarized light for the presence of residual stresses, as residual stresses in excess of 800 psi will produce crazing in less than 10 years.[17]

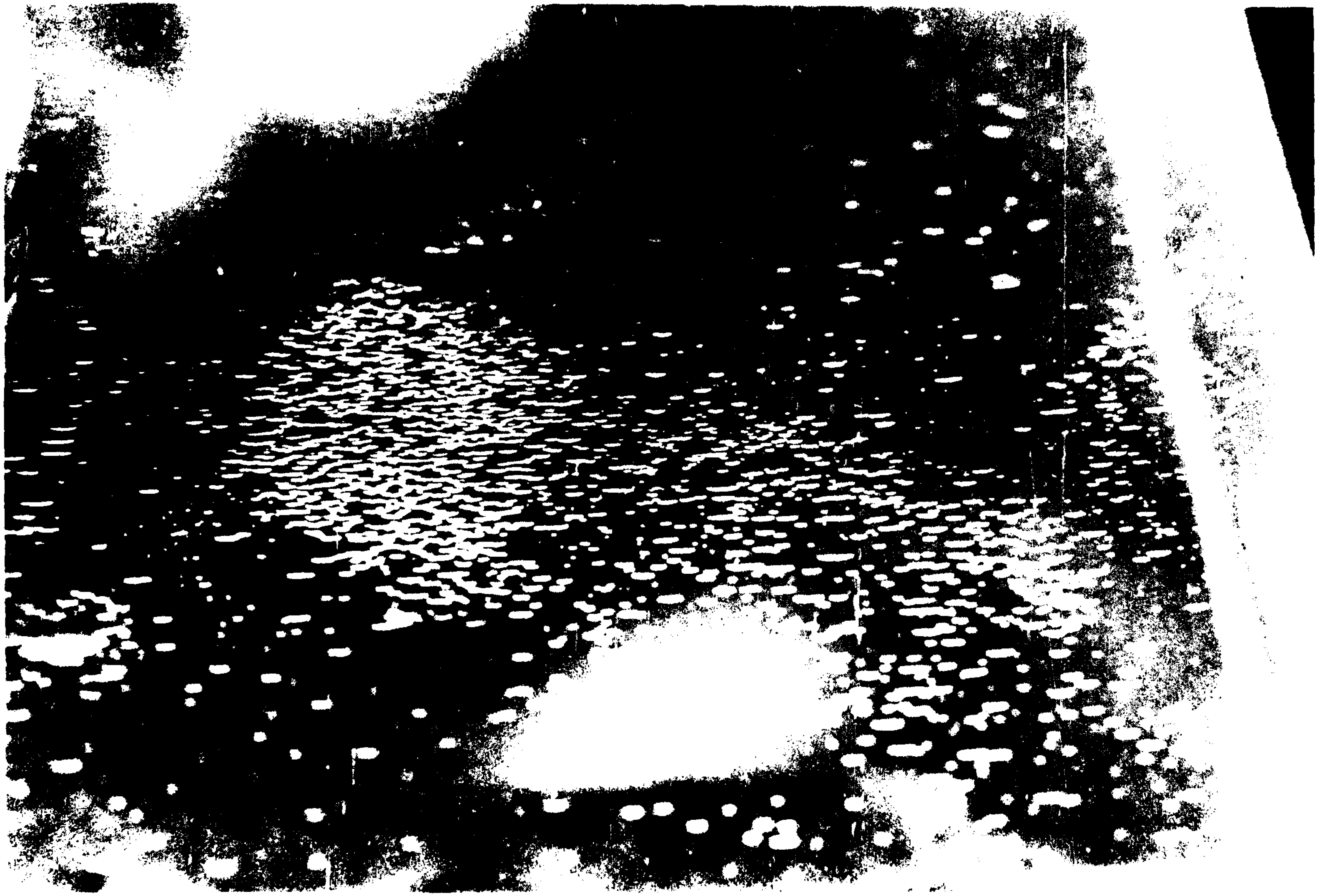


Figure 1. Typical crazing on the exterior surface of a weathered, acrylic plastic structure.

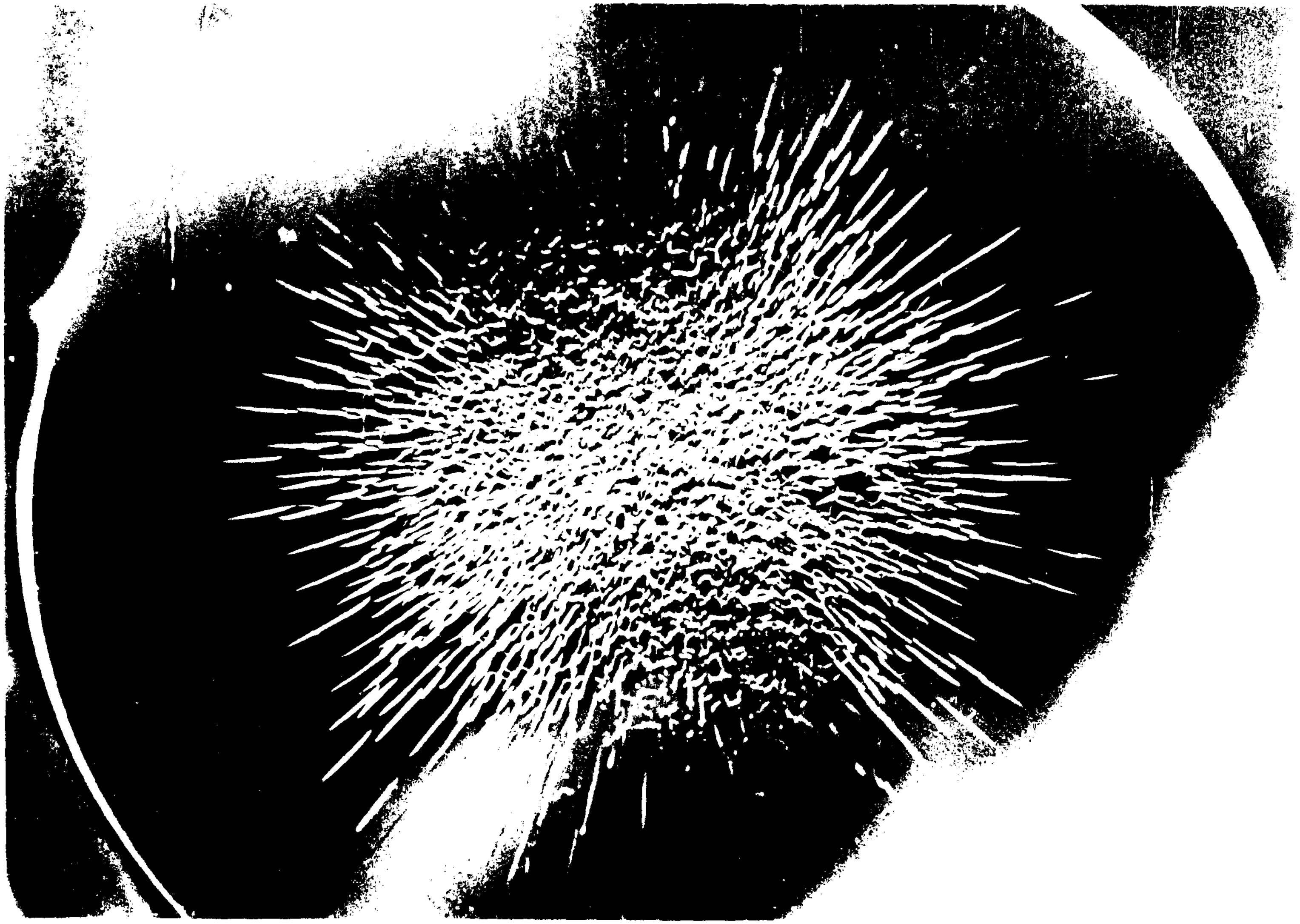


Figure 2. Crazing on the exterior surface of an acrylic plastic plane disc window under sustained flexure stress of 2000 psi after 5 minutes of exposure to ethyl alcohol.

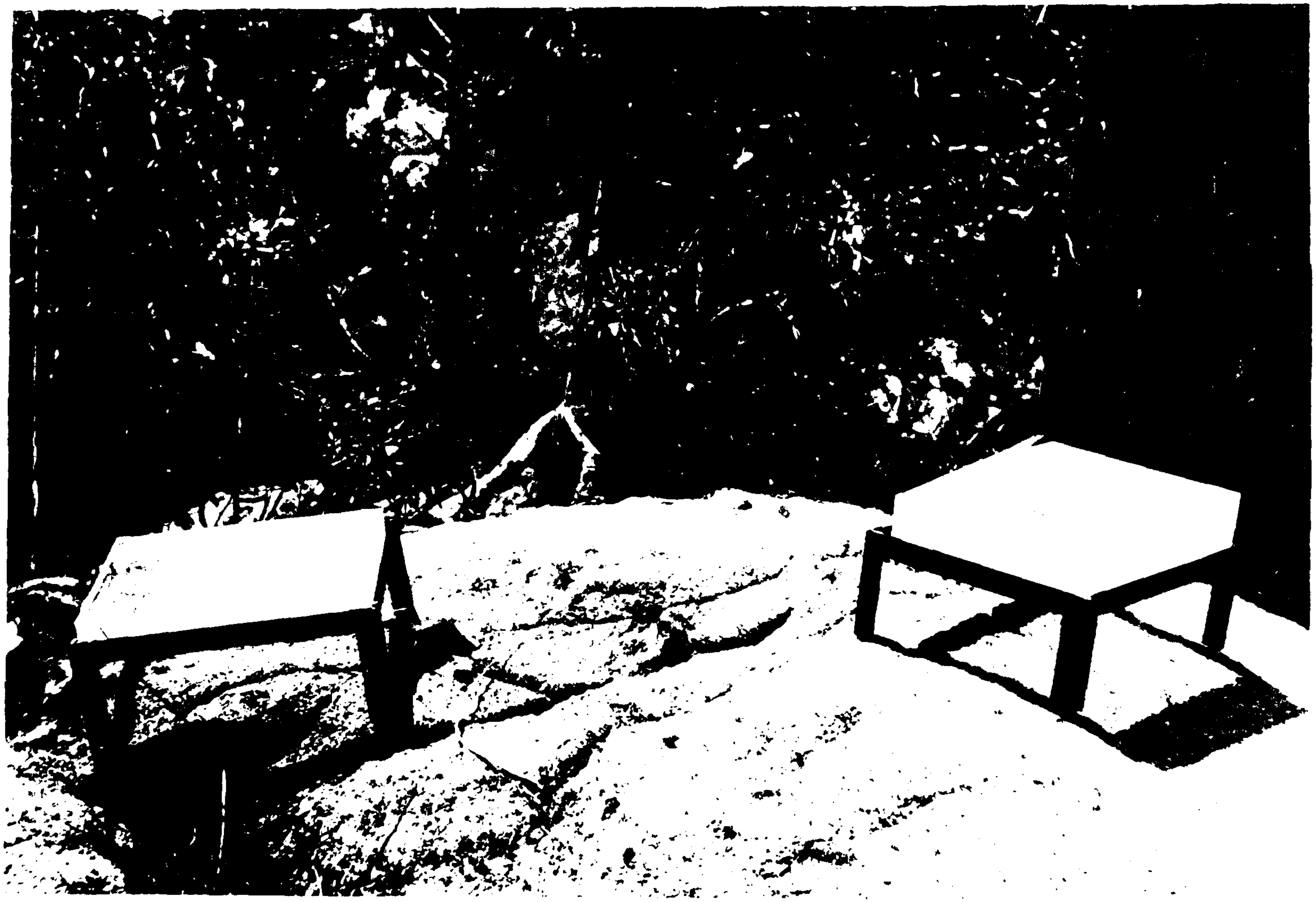
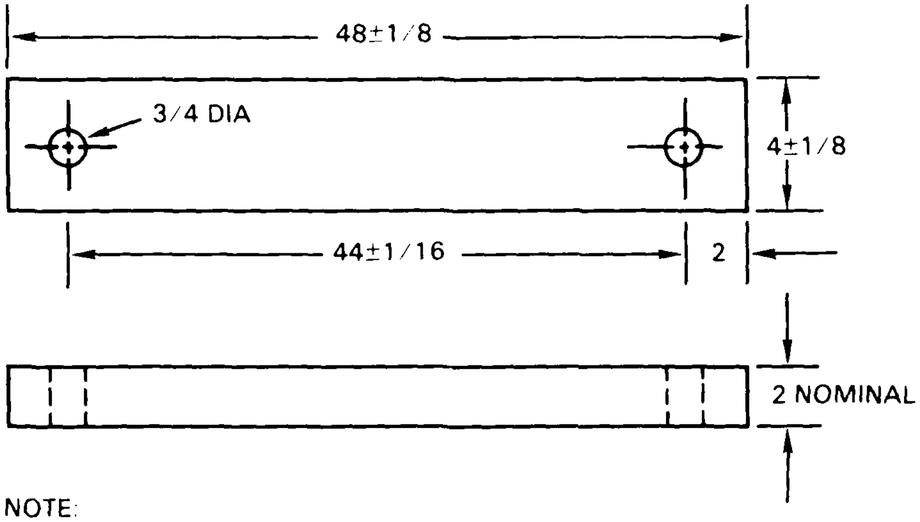


Figure 3. Thick weathering specimens cut from 2- and 4-inch-thick acrylic plastic plates after placement at test location in El Cajon, California.

Figure 4. Text fixture for application of bending moments to several 2- by 22- by 0.25-inch-thick acrylic strips. Note that Dr. Stachiw is wetting the top surface of test specimens stressed to 2000 psi with ethyl alcohol.



NOTE:

1. All the test bars to be cut from a single sheet of 2 inch-thick Plexiglas G
2. The edges of the test .ars to be saw cut, sanded smooth, and polished
3. After polishing, anneal the test bars at 190°F for 24 hours

Figure 5. Dimensions of test beams for flexure testing cut from 2-inch-thick acrylic plastic plate.

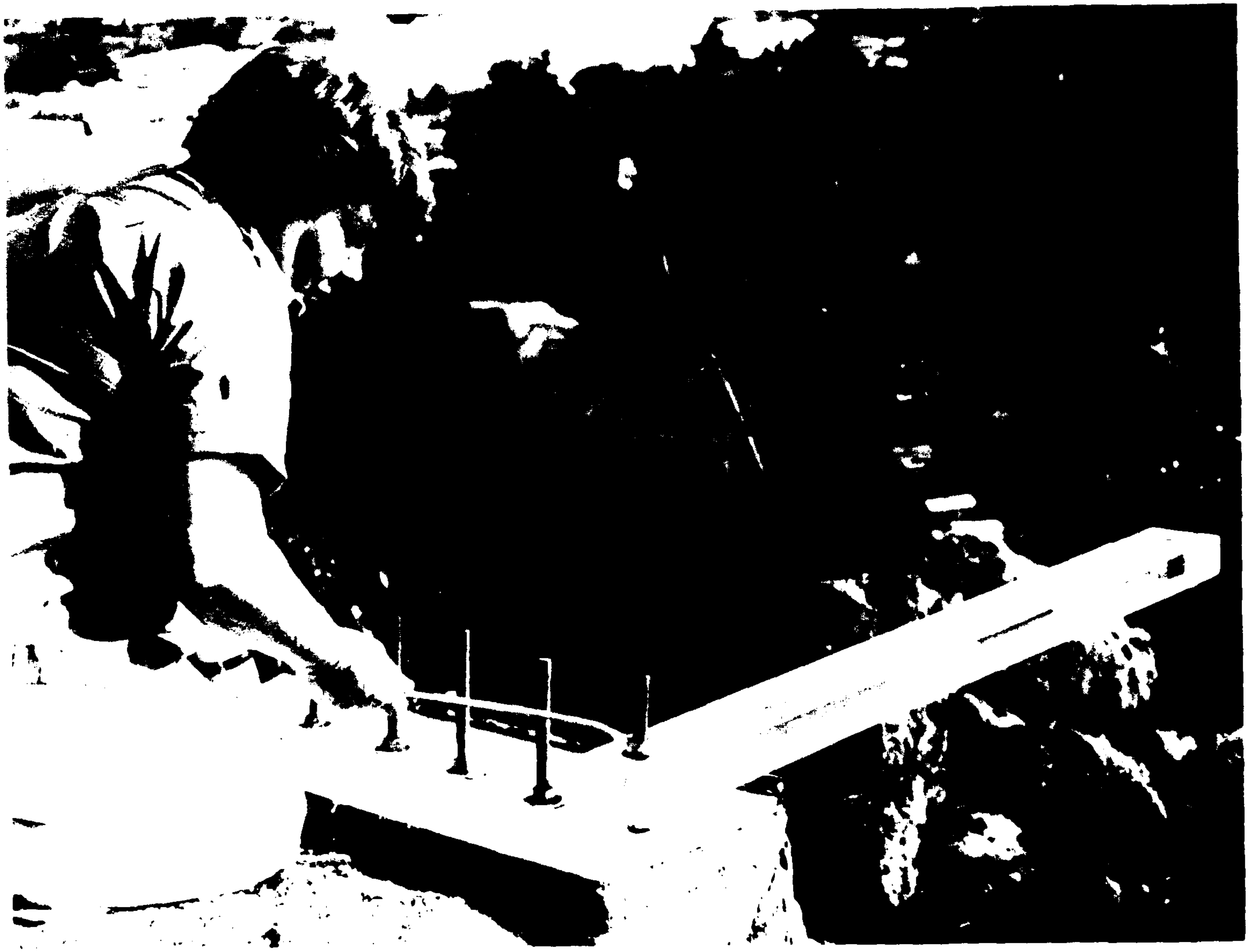


Figure 6. *Anchoring* of 4- by 48- by 2-inch-thick test beams in the outdoor weathering flexure test fixture.

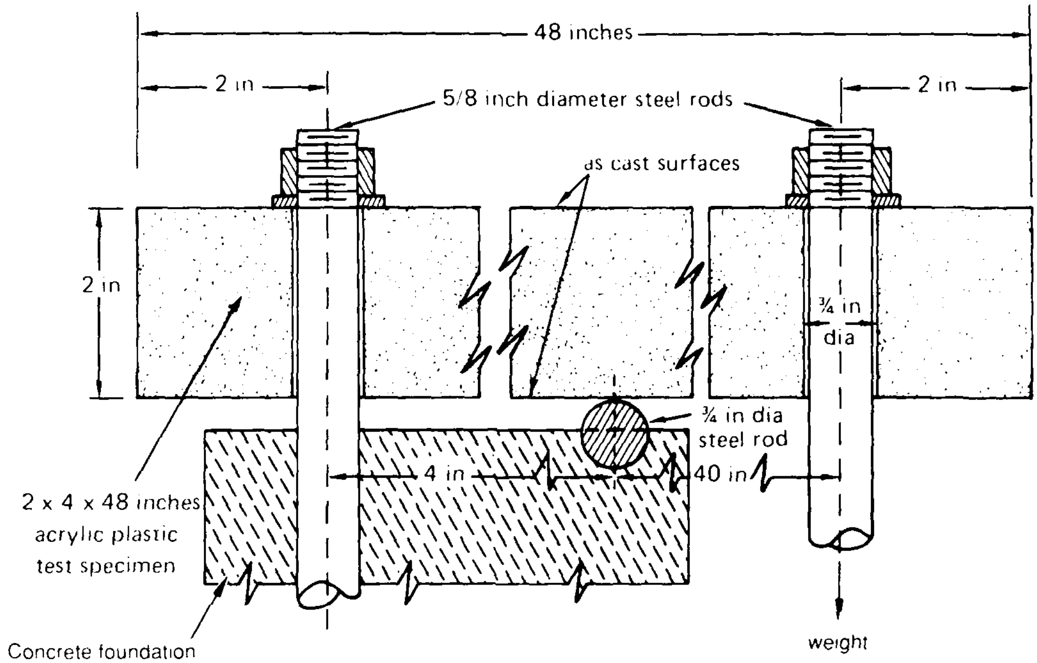


Figure 7. Arrangement for application of bending moments to 4- by 48-by 2-inch-thick acrylic plastic test beams.

Figure 8. Completed installation of the flexure test beams at the Stachiw Associates' outdoor weathering test facility located in El Cajon. Note that each of the cantilever beams is subjected to a different size of dead load.

Figure 9. The deflection of each 4- by 48- by 2-inch-thick beam was recorded periodically by placing a water level on the top surface of the beam at its base and measuring the distance between the tip of the deflected beam and the horizontal level.

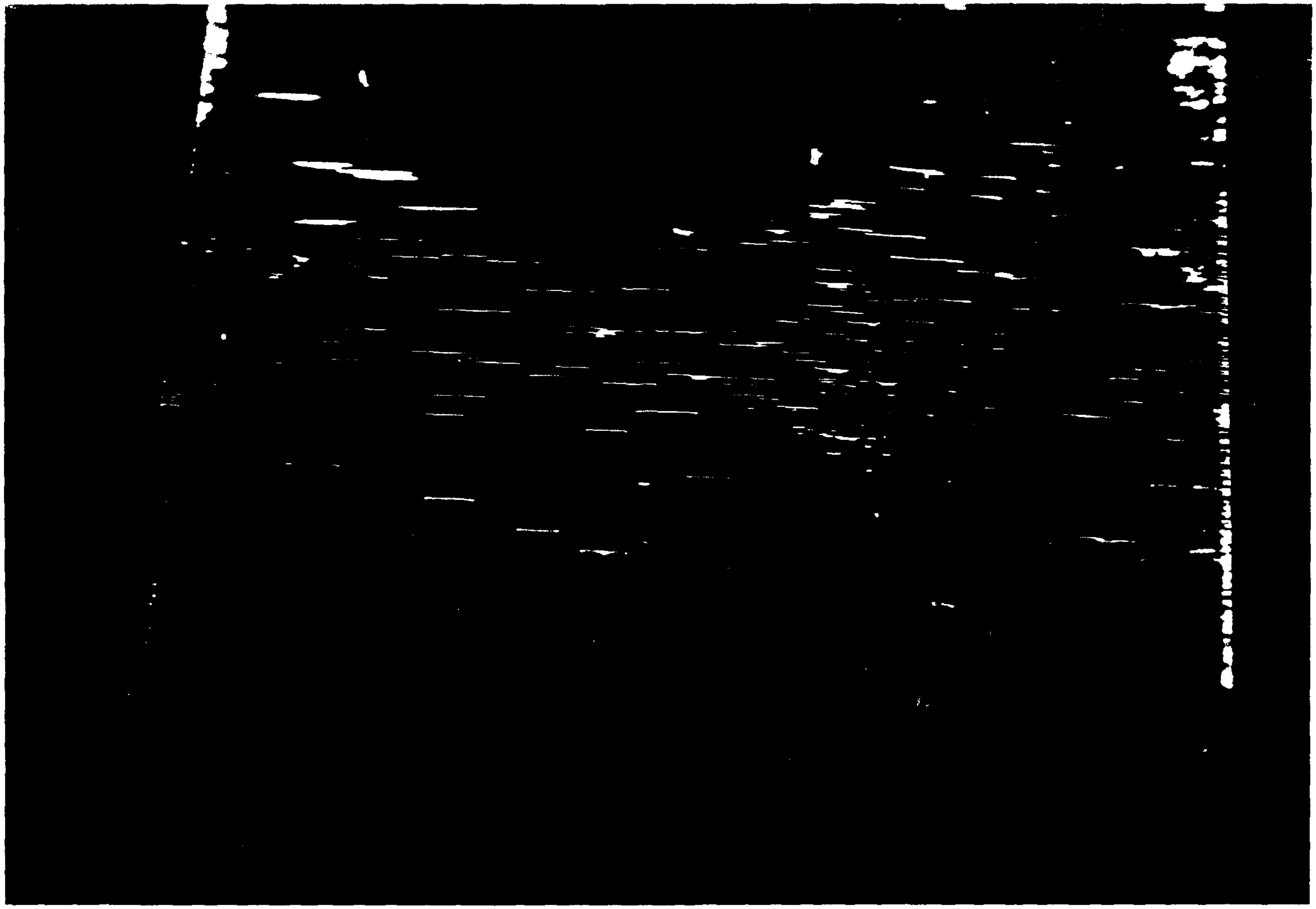


Figure 10. Crazing of the upper surface on the 2- by 22- by 0.25-inch-thick flexure specimen after 20 minutes of sustained 2000-psi flexure stress and continuous wetting by ethyl alcohol. Note that the crazing is oriented at right angles to the direction of principal flexure stress.

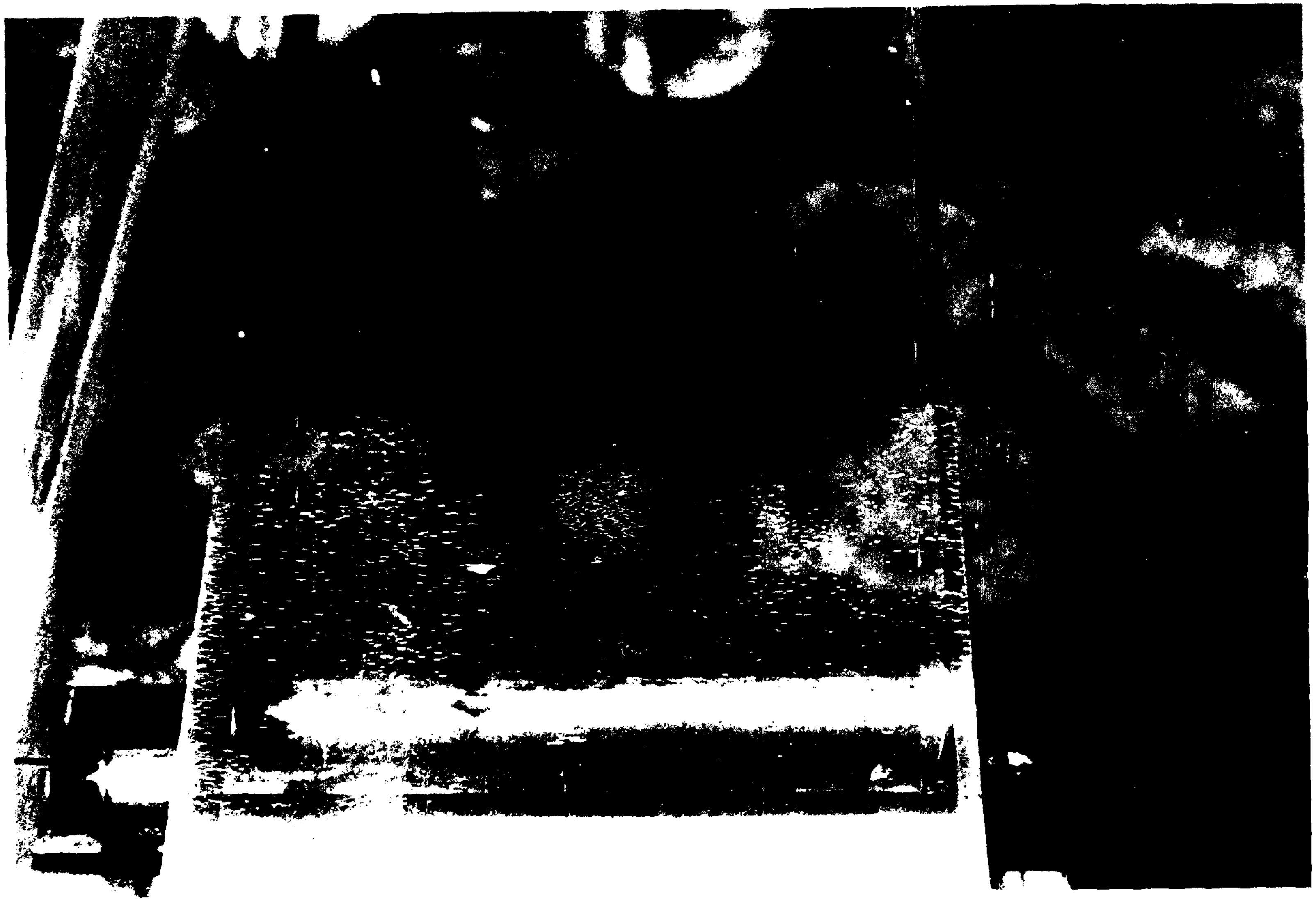


Figure 11. Crazing on the upper surface of the 4- by 48- by 2-inch-thick test beam No. 1 after 4 years of sustained flexure loading as a cantilever beam; the flexure stress above the fulcrum is 2240 psi.

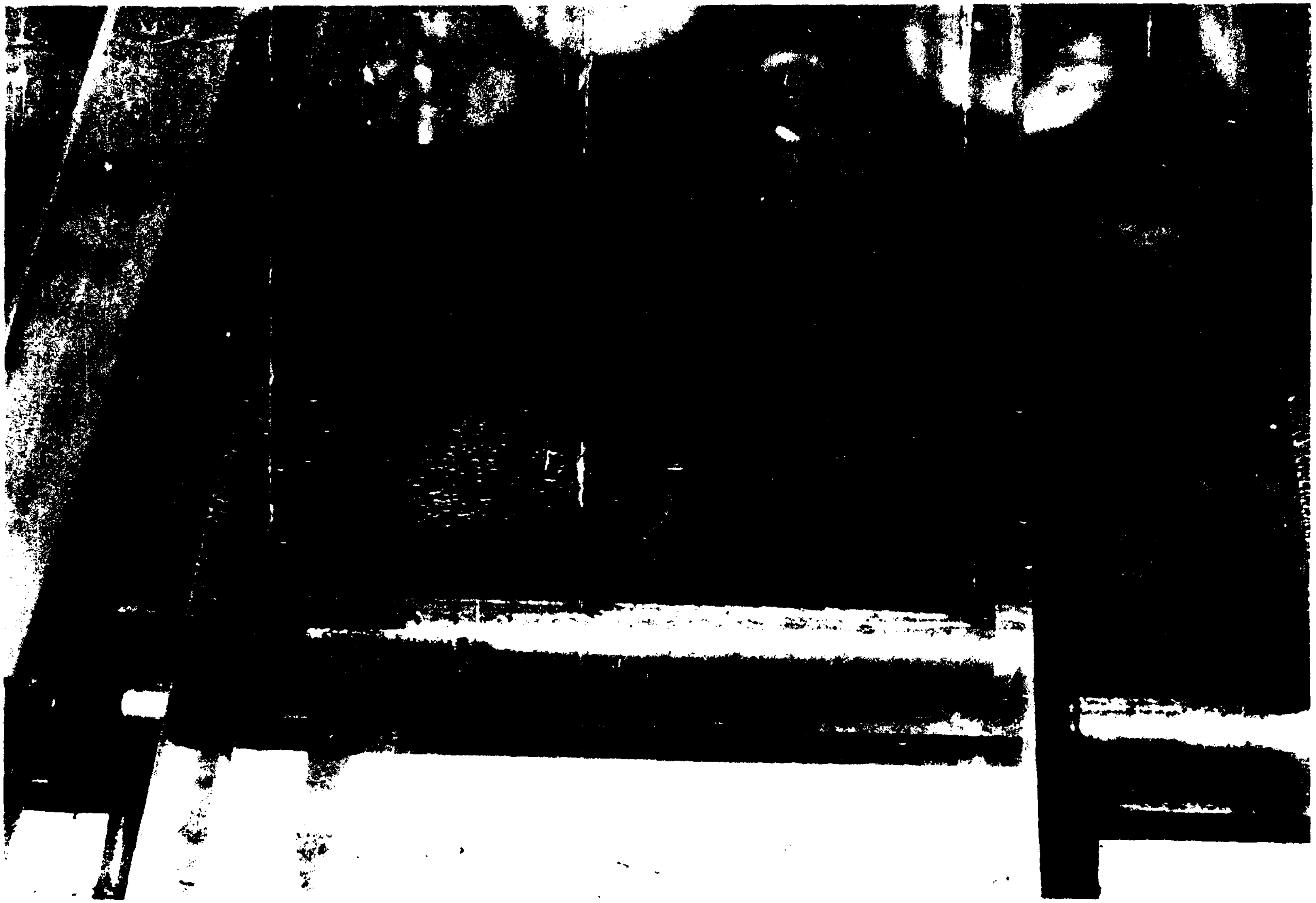


Figure 12. Crazing on the upper surface of the 4- by 48- by 2-inch-thick test beam No. 2 after 4 years of sustained flexure loading as a cantilever beam; the flexure stress above the fulcrum is 1960 psi.

Figure 13. Crazing on the upper surface of the 4- by 48- by 2-inch-thick test beam No. 3 after 4 years of sustained flexure loading as a cantilever beam; the flexure stress above the fulcrum is 1570 psi.

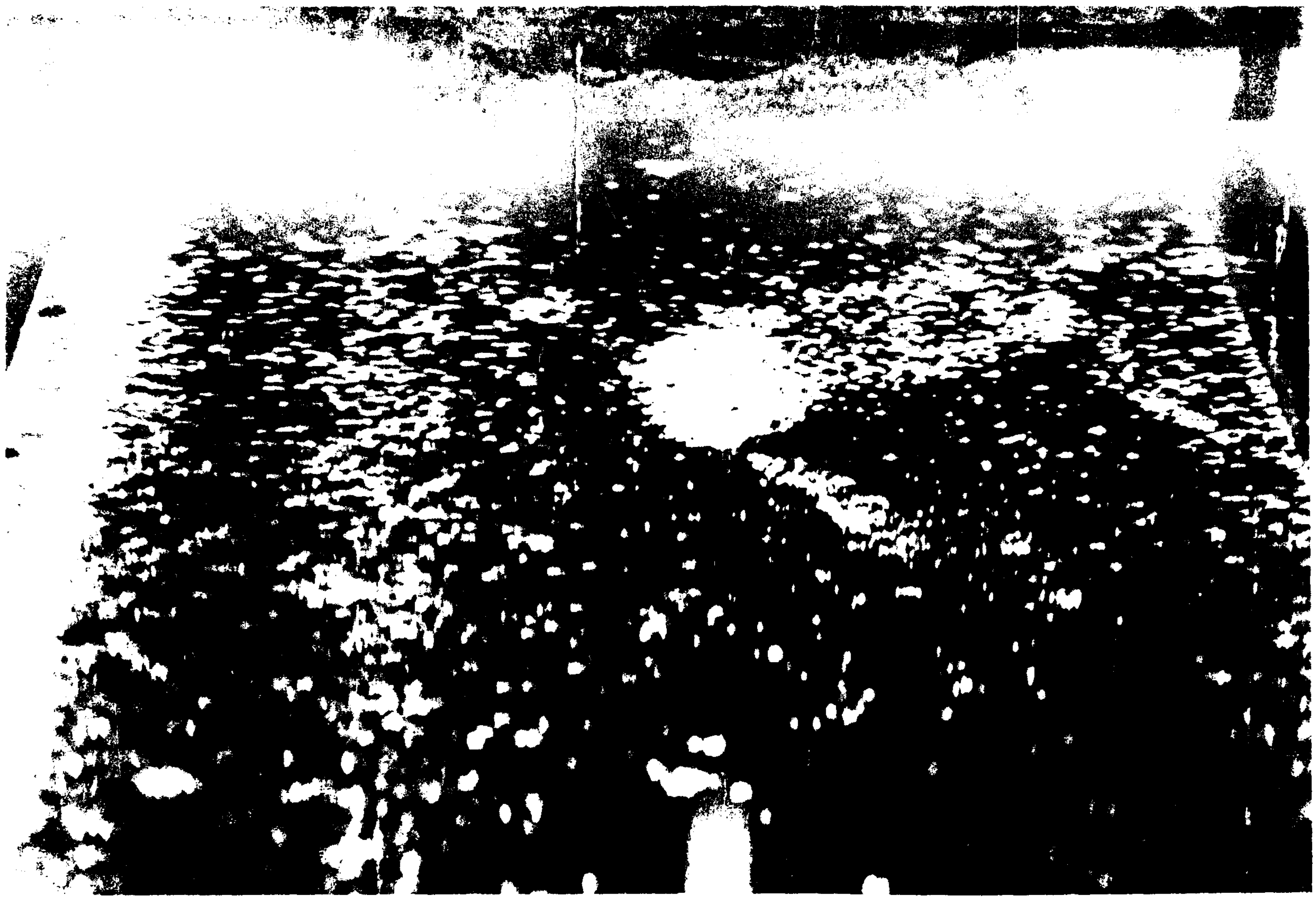


Figure 14. Crazing on the upper surface of the 4- by 48- by 2-inch-thick test beam No. 1 after 5 years of sustained flexure loading as a cantilever beam; the crazing was photographed from below the beam.

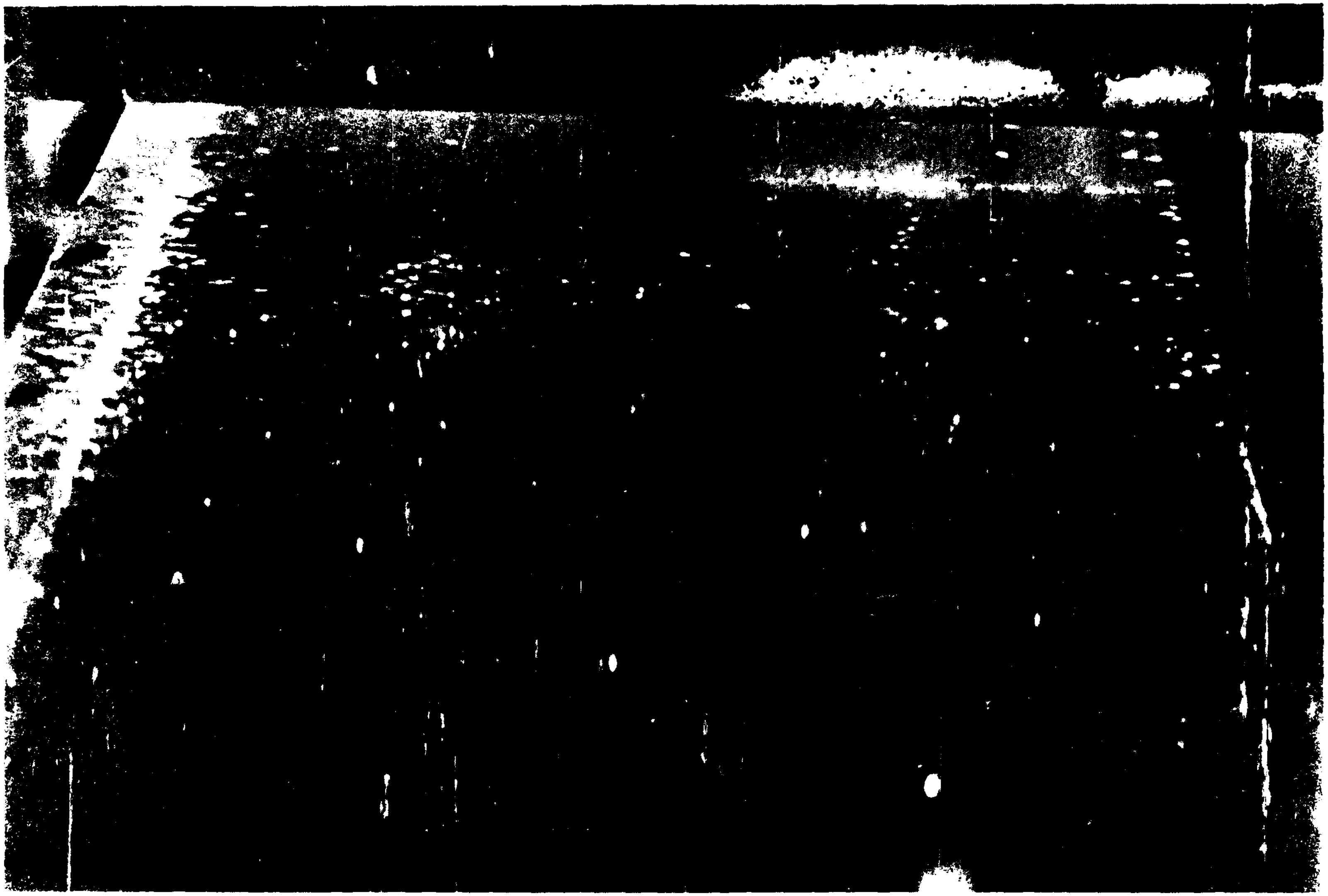


Figure 15. Crazing on the upper surface of the 4- by 48- by 2-inch-thick test beam No. 2 after 5 years of sustained flexure loading as a cantilever beam; the crazing was photographed from below the beam.

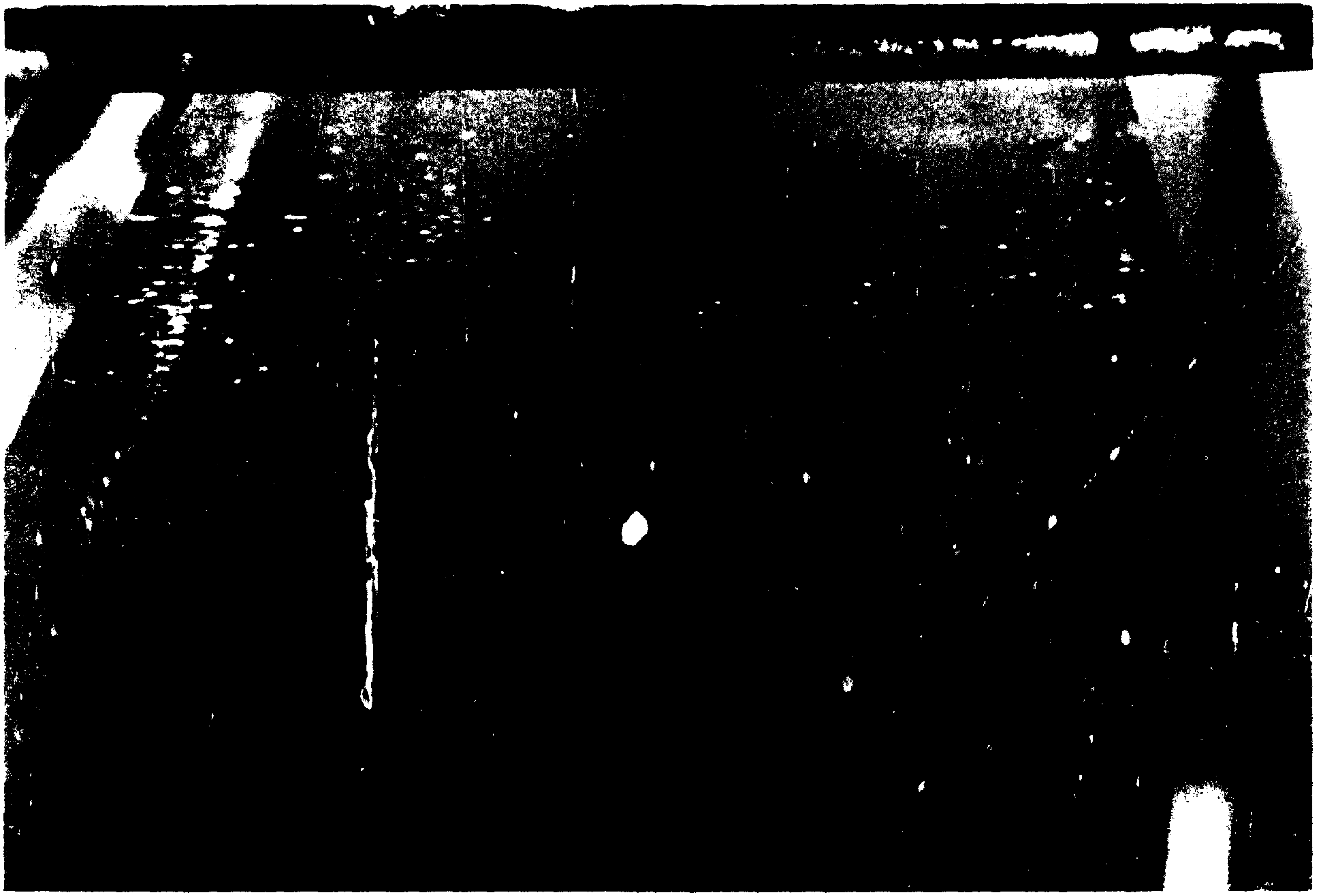


Figure 16. Crazing on the upper surface of the 4- by 48- by 2-inch-thick test beam No. 3 after 5 years of sustained flexure loading as a cantilever beam; the crazing was photographed from below the beam.

Figure 17. Note the absence of crazing on test beam No. 4 after 5 years of sustained flexure loading as a cantilever beam; the flexure stress above the fulcrum is 1200 psi. The beam was photographed from below.

Figure 18. The 4- by 48- by 2-inch-thick test beam under sustained 2240-psi flexure stress and outdoor weathering failed catastrophically after 9 years.

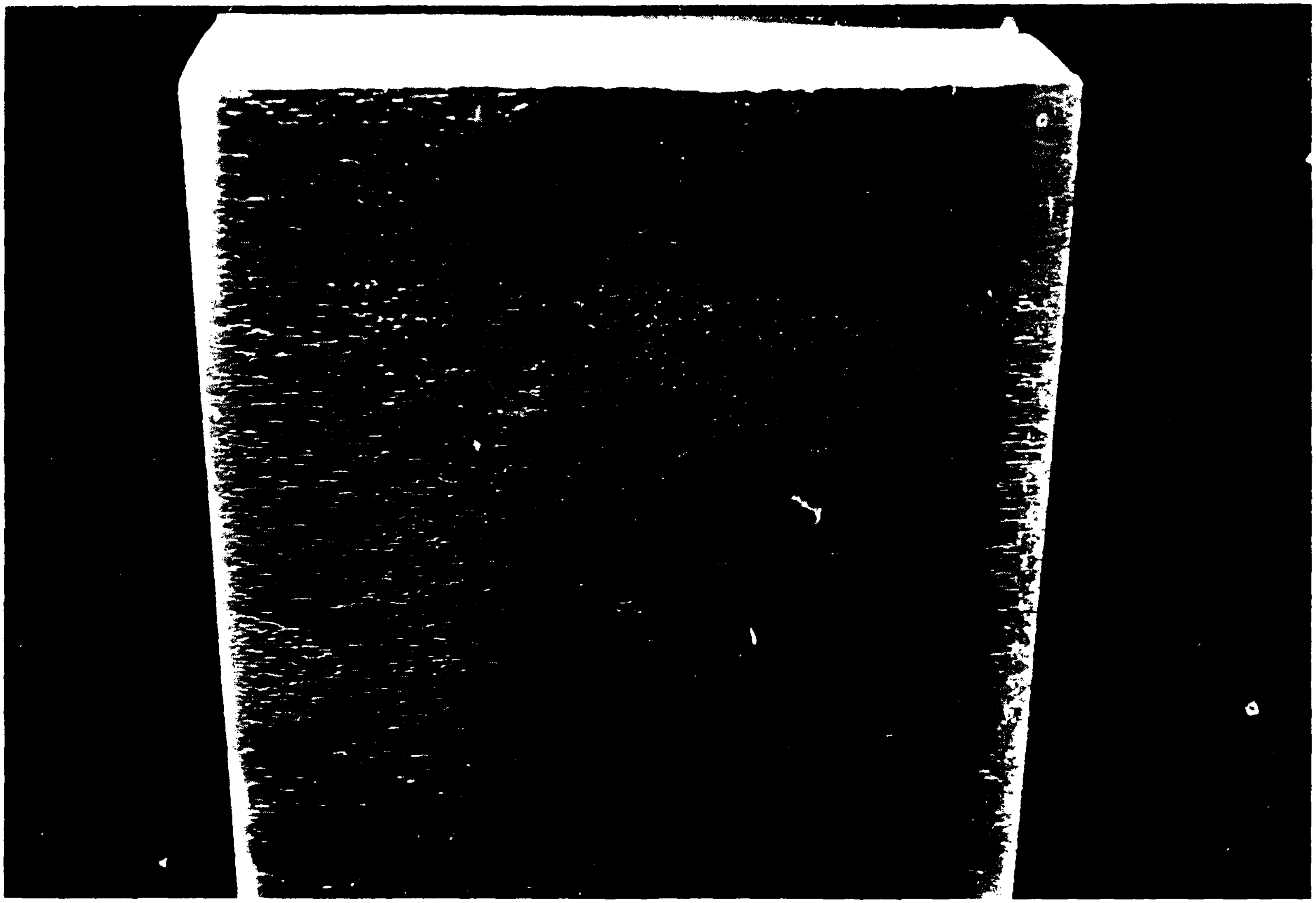


Figure 19. Crazing on test beam No. 1 after 9 years of sustained flexure loading as a cantilever beam. The stress above the fulcrum was 2240 psi.

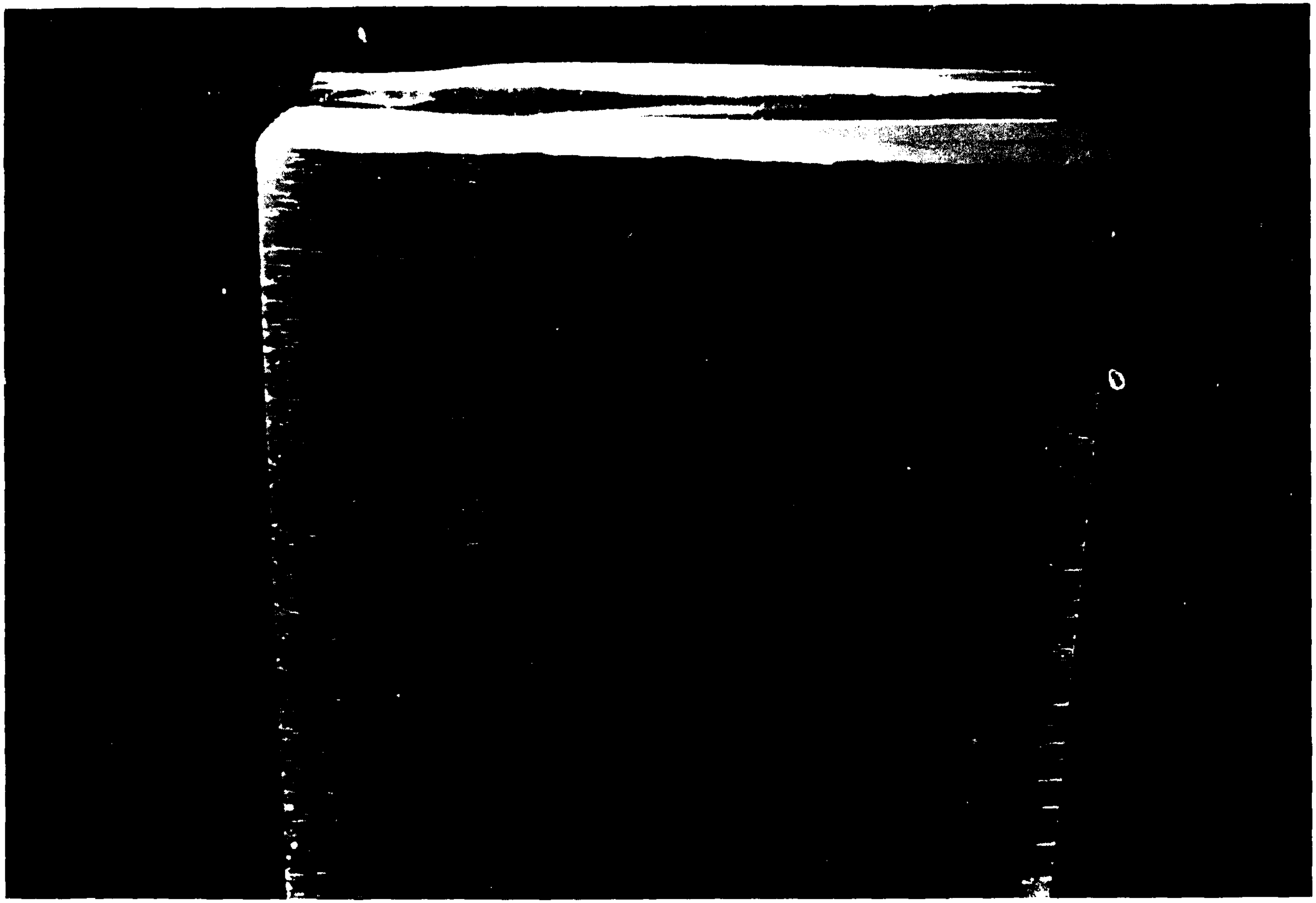


Figure 20. *Crazing on test beam No. 2 subjected to sustained flexure stress of 1960 psi for 10 years.*

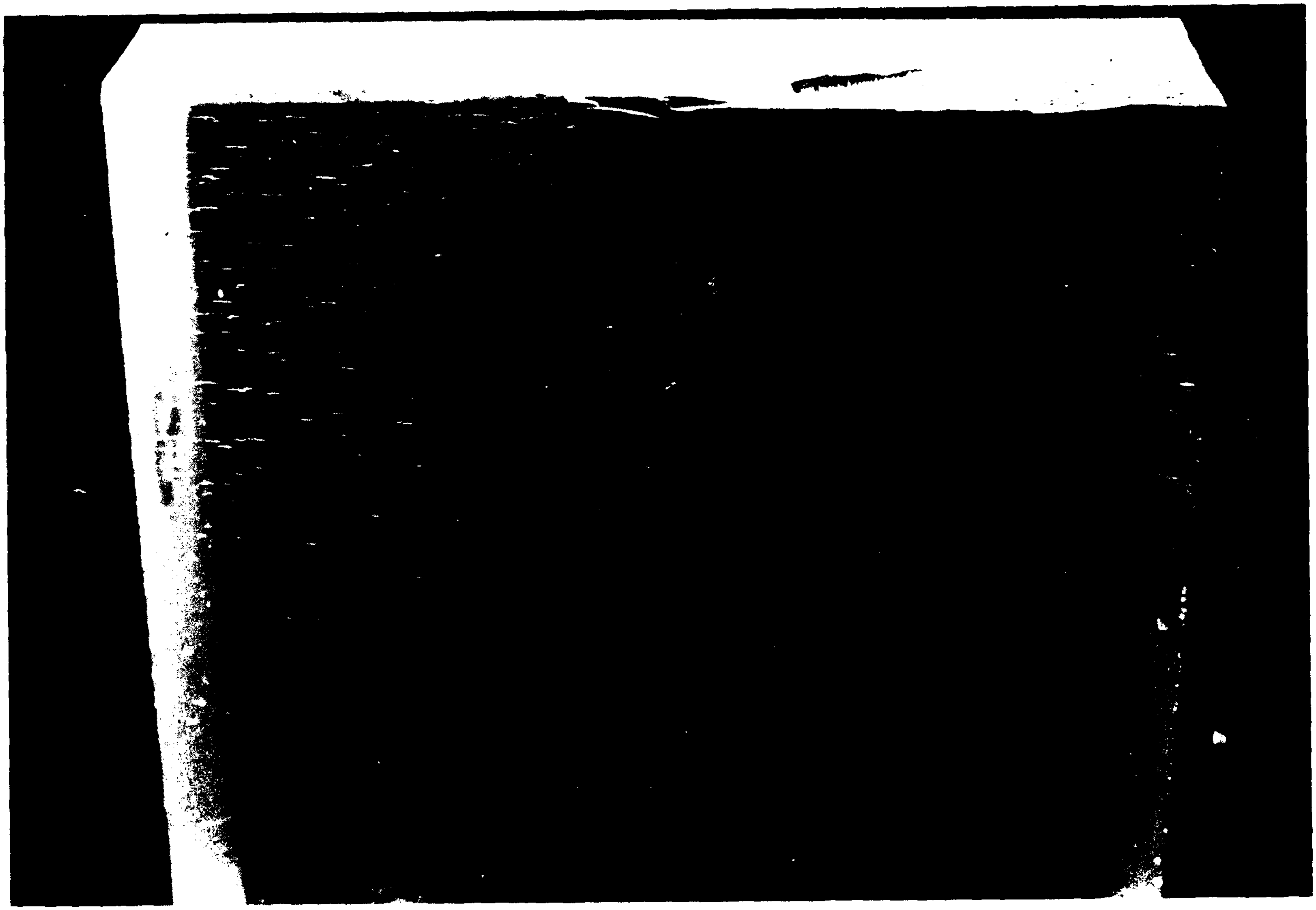


Figure 21. Crazing on test beam No. 3 subjected to sustained flexure stress of 1570 psi for 10 years.

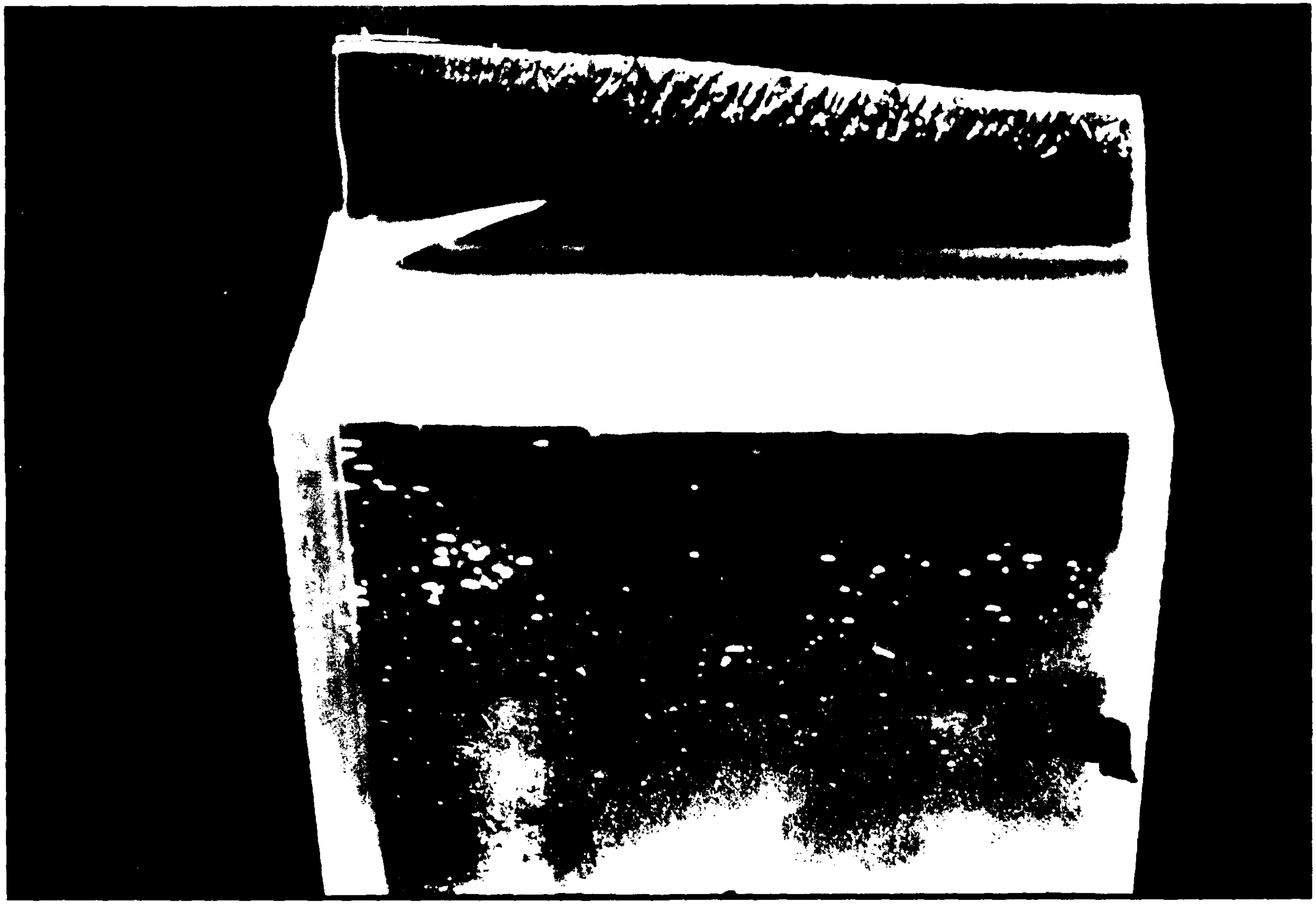


Figure 22. Crazing on test beam No. 4 subjected to sustained flexure stress of 1200 psi for 10 years.

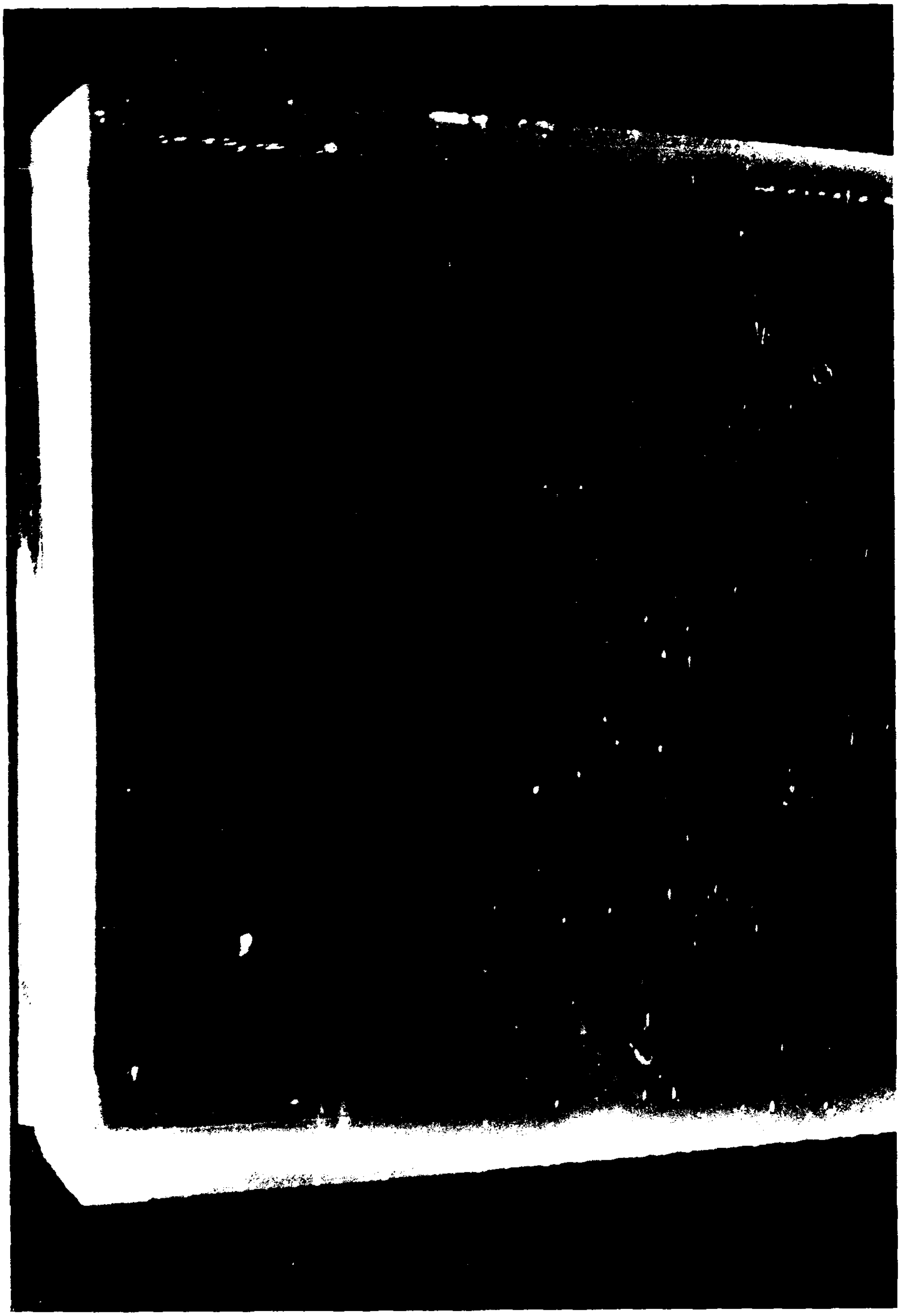


Figure 23. Crazing on test beam No. 5 subjected to sustained flexure stress of 970 psi for 10 years.

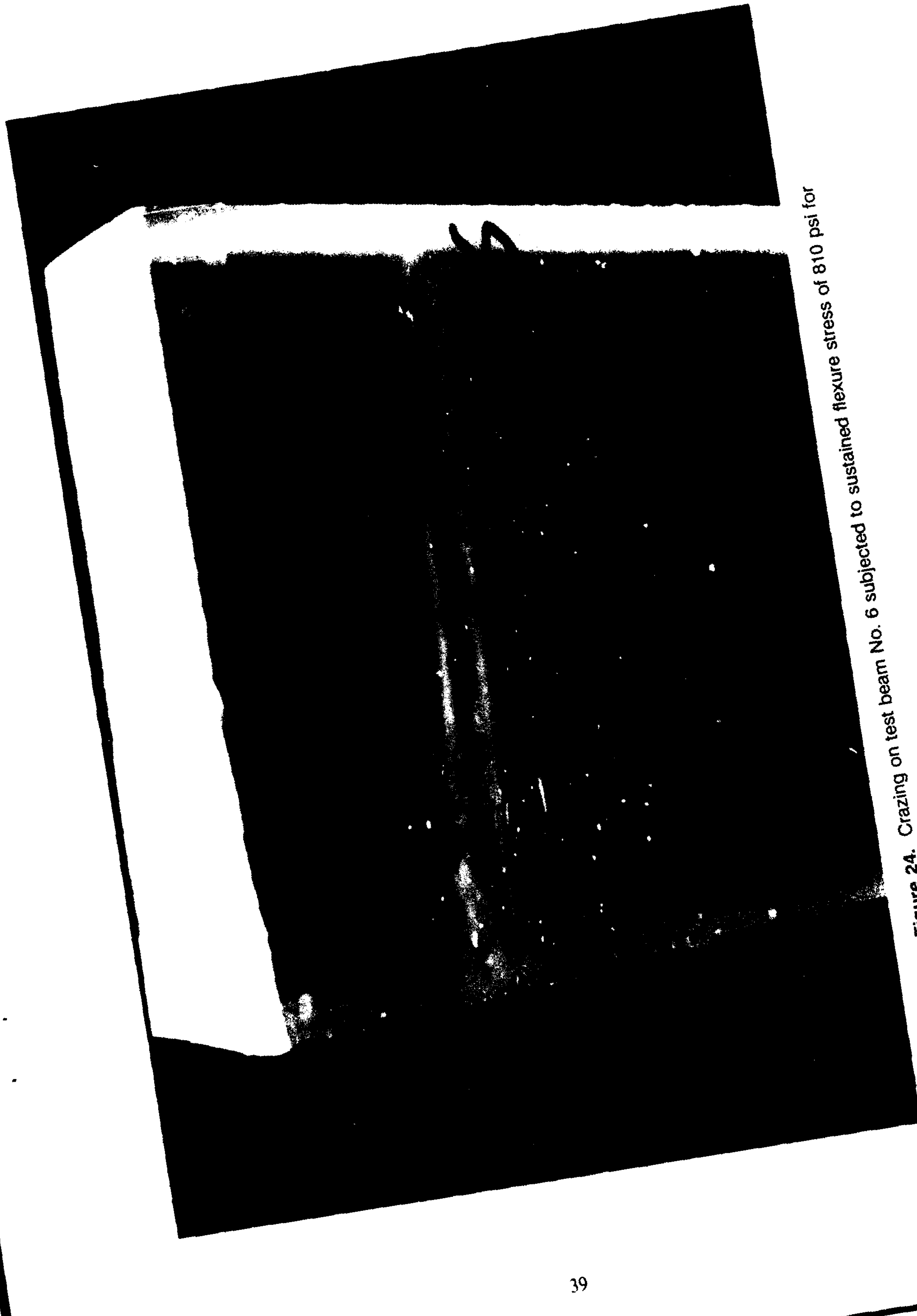


Figure 24. Crazing on test beam No. 6 subjected to sustained flexure stress of 810 psi for 10 years.

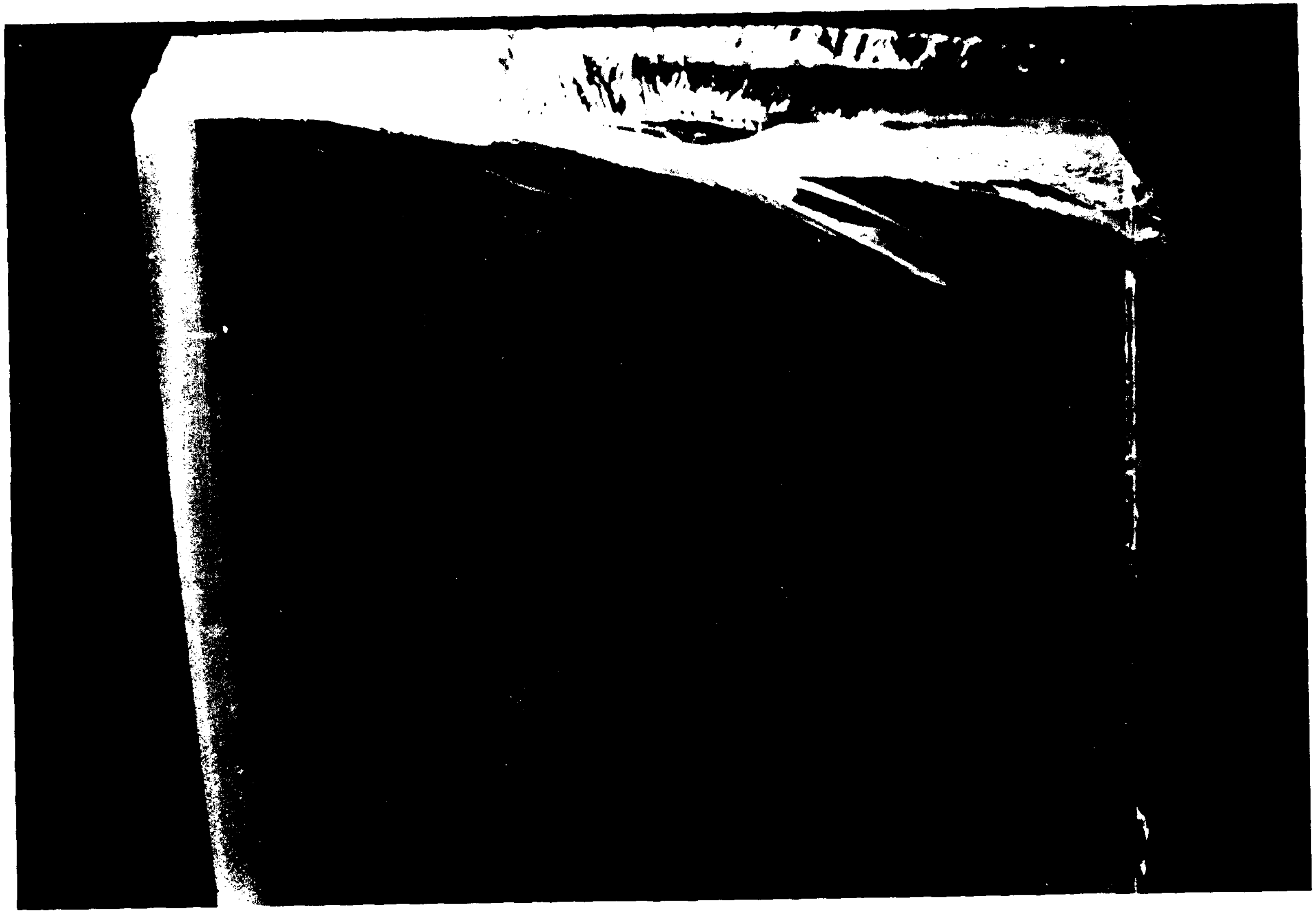


Figure 25. The 4- by 48- by 2-inch-thick test beam after 10 years of weathering and short-term flexure loading to catastrophic failure. Note the total absence of crazing on the surfaces of the beam.

Figure 26. All of the 4- by 48- by 2-inch-thick test beams were, after 10 years of weathering, loaded to failure to determine the effective flexure strength of the weathered plastic. The highest effective strength was found on *unstressed* specimen (No. 7), while the lowest one was found in the specimen subjected to the highest sustained flexure stress (No.2).

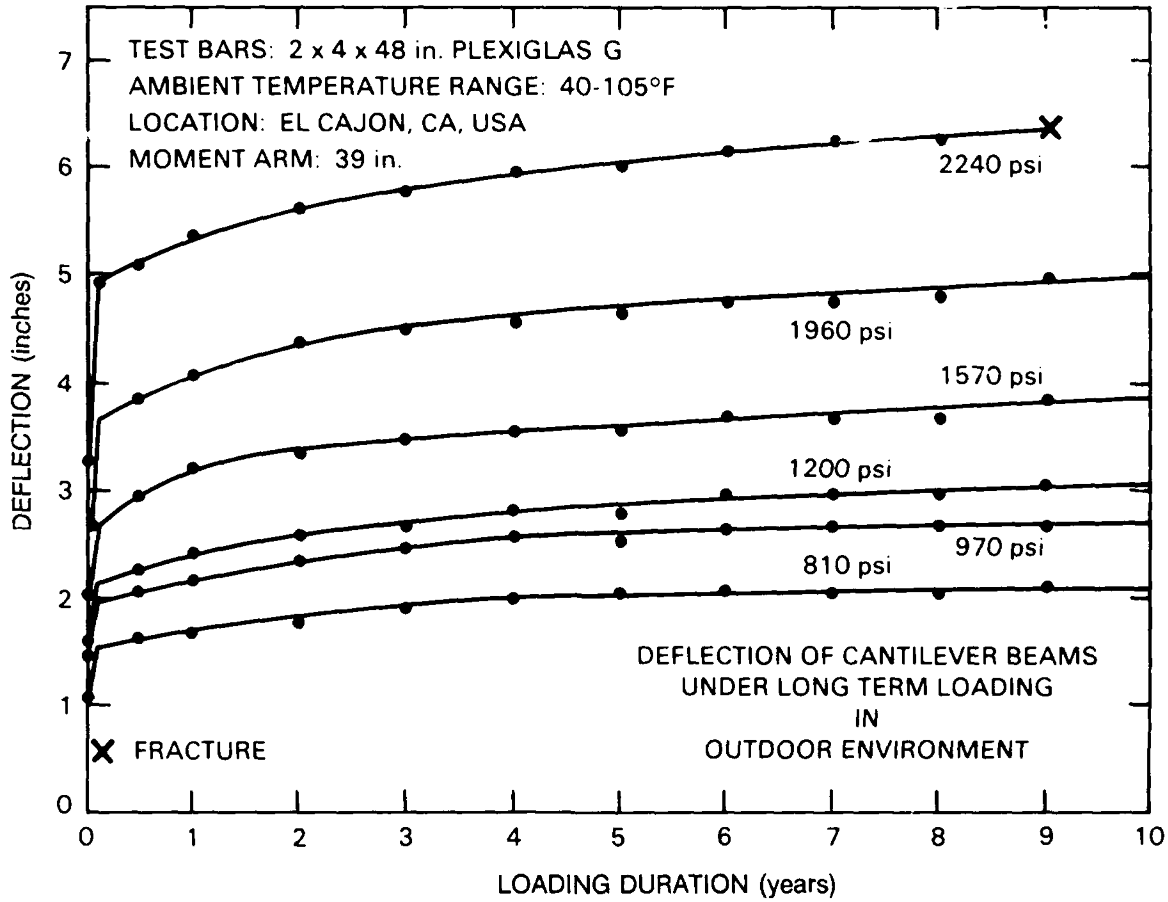


Figure 27. Deflections of the cantilevered test beams at their tips during sustained flexure loading in outdoor environment. The test beam under highest flexure loading failed in 9 years after extensive crazing.

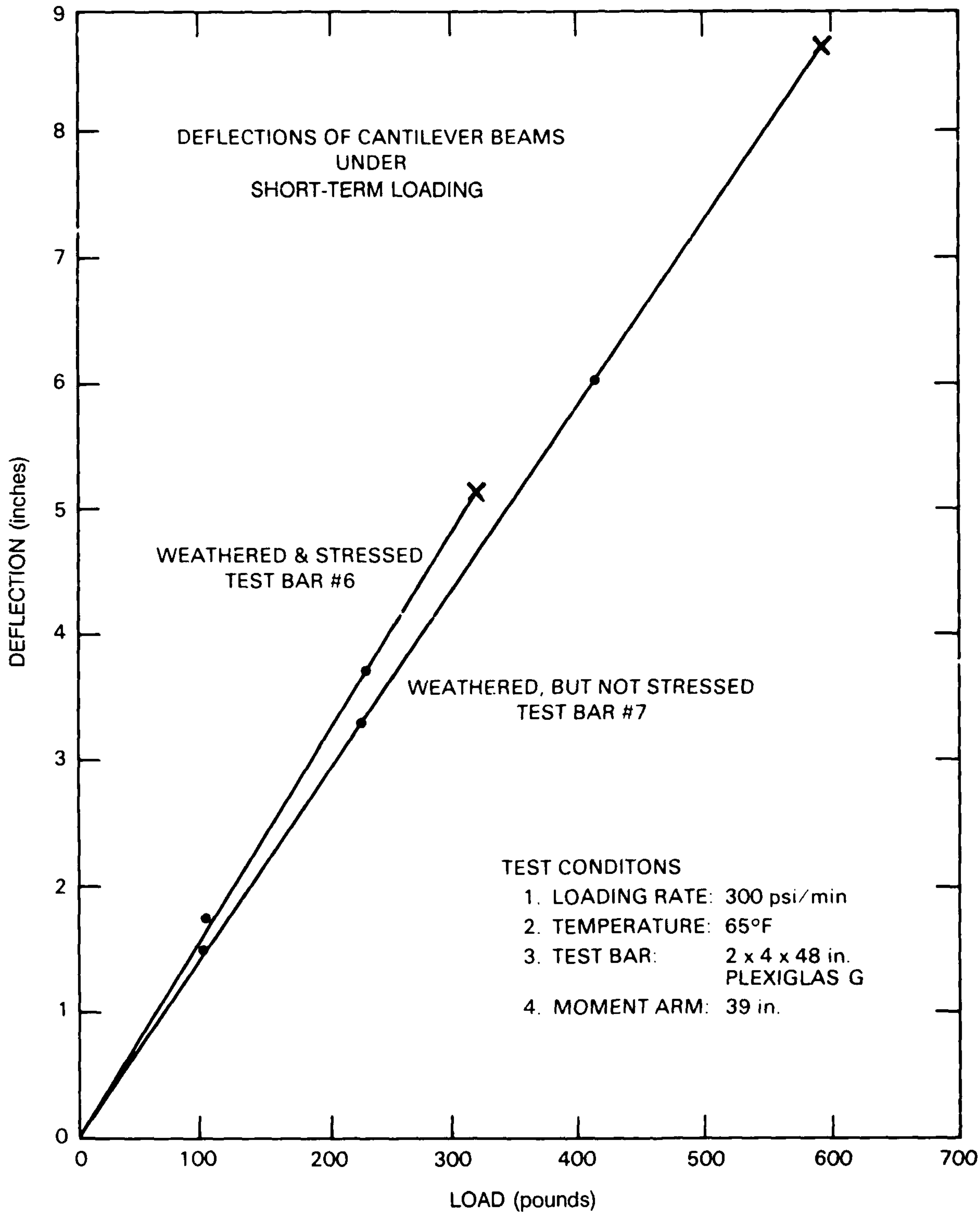


Figure 28. Deflections of cantilevered test beams during short-term loading to destruction. Note the significant difference in effective strength between the two weathered, crazing free beams: one unstressed and the other one under sustained flexure stress of 810 psi for 10 years.

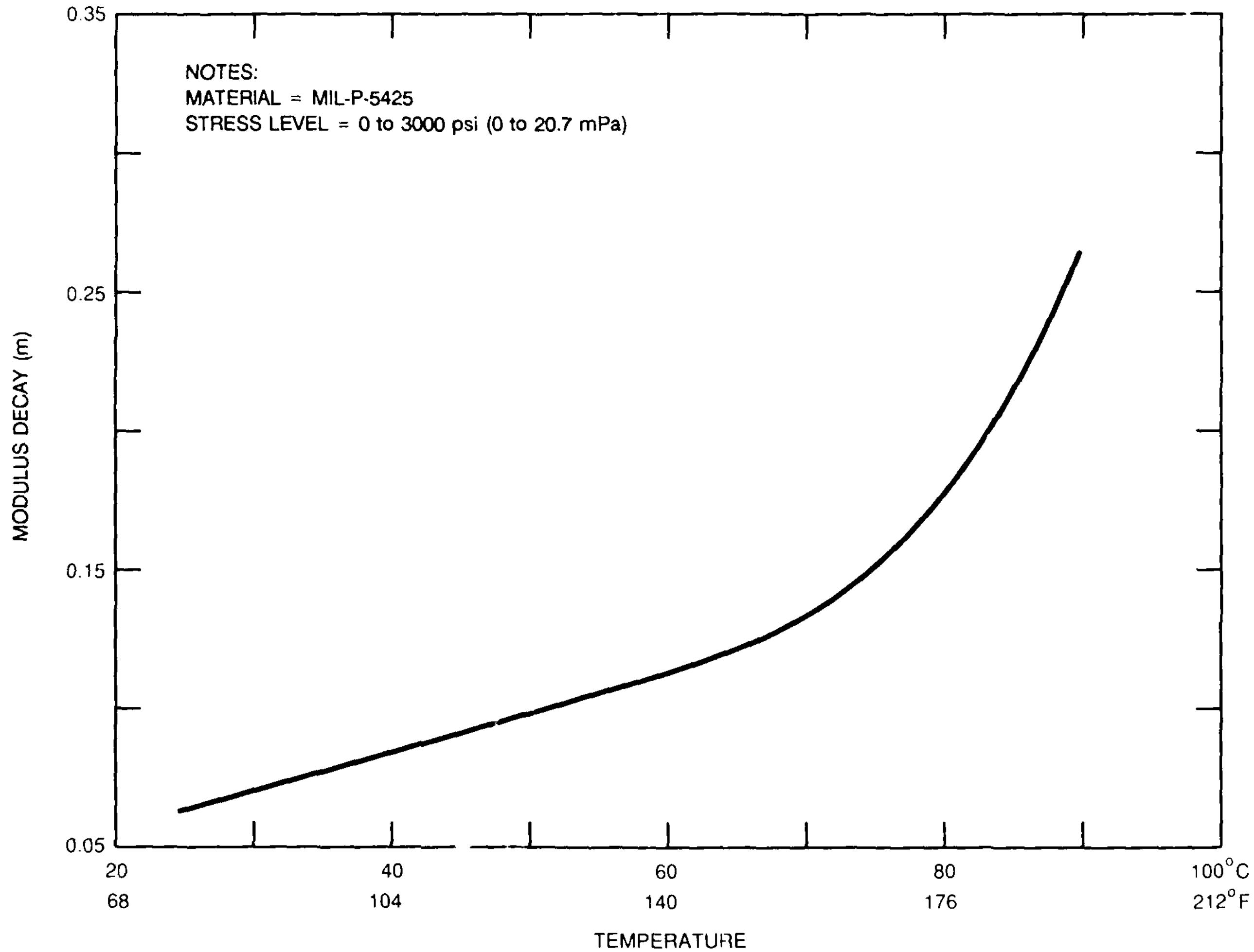


Figure 29. Decay of effective modulus of acrylic plastic (M) as a function of ambient test temperature.

Table 1. Physical properties of acrylic plastic prior to machining of test beams.

Physical Property		Location						
Test Type		Top Surface	0.005 Below Top Surface	0.020 Below Top Surface	Mid-thickness	0.020 Above Bottom Surface	0.005 Above Bottom Surface	Bottom Surface
ASTM D-638	Tensile Strength (psi)	10,400	——	——	10,500	——	——	10,600
ASTM D-790	Flexure Strength (psi)	17,200	——	——	17,400	——	——	17,300
ASTM D-695	Compressive Yield (psi)	17,200	——	——	17,100	——	——	17,000
ASTM D-732	Shear Strength (psi)	10,200	——	——	10,300	——	——	10,300
ASTM D-621	Deformation Under Load 24 hrs at 122°F and 400 psi	0.46	——	——	0.47	——	——	0.48
ASTM D-256	Izod Impact	0.37	——	——	0.38	——	——	0.36

Material: Plexiglas G 4 in. and 2 in. thick plates

Weathering Specimens: 12 x 12 x 4 and 12 x 12 x 2 in.

Test Specimens: ASTM

Table 2. Effect of outdoor weathering on flexural strength of acrylic plastic plates.

	Location						
Length of Exposure	Top Surface	0.005 Below Top Surface	0.020 Below Top Surface	Mid-thickness	0.020 Above Bottom Surface	0.005 Above Bottom Surface	Bottom Surface
0 year	17,000	17,300	17,300	17,400	17,300	17,200	17,100
5 year	$15{,}600^{E}$	$16{,}800^{E}$	$16{,}200^{E}$	$17{,}400^{E}$	$16{,}900^{E}$	$17{,}100^{E}$	$15{,}000^{E}$
10 year	^{E}	— —	— —		— —	— —	
	$10{,}600^{H}$	— —	— —	$17{,}800^{H}$	— —	— —	$15{,}000^{H}$
	$5{,}900^{L}$	— —	— —	$17{,}200^{L}$	— —	— —	$11{,}000^{L}$
	$11{,}500^{S}$	$14{,}700^{S}$	$16{,}800^{S}$	$17{,}000^{S}$	$16{,}700^{S}$	$15{,}800^{S}$	$15{,}400^{S}$

Material: Plexiglas G

Weathering Specimens: 12 x 12 x 4 in.

Test Location: E - El Cajon
L - Linkport
H - Houston
S - San Diego

Test Position: Horizontal

Flexure Test: The indicated surfaces were flexed in tension

Flexure Strength: psi, per ASTM D-790

Table 3. Cantilever beams under long-term loading in outdoor environment.

Test Bar	Maximum Flexure Stress (psi)	Deflection Upon Loading (inches)	Deflection After 1 hr (inches)	Deflection After 24 hrs (inches)	Deflection After 10 yrs (inches)	Deflection Upon Unloading (inches)	Deflection 1 hr After Unloading (inches)	Deflection 24 hrs After Unloading (inches)
#1	2240	3.250	3.82	4.00	6.25	——	——	——
#2	1960	2.625	2.85	3.04	5.00	2.68	2.375	2.06
#3	1570	1.908	2.095	2.22	3.875	2.00	1.700	1.50
#4	1200	1.408	1.533	1.72	3.09	1.625	1.370	1.125
#5	970	1.375	1.600	1.625	2.82	1.680	1.500	1.187
#6	810	0.97	1.200	1.220	2.125	1.125	1.00	0.810
#7	000	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Test Conditions
- Test Bars: 2 x 4 x 48 in.
- Material: Plexiglas G
- Moment Arm: 39 in.
- Temperature: 40-105°F range
- Test Location: Outdoors, exposed to direct sunshine, El Cajon, CA

Table 4. Remaining strength of cantilever beams after 10 years' sustained loading in outdoor environment.

Test Bar	Maximum Flexure Stress Sustained for 10 yrs (psi)	Maximum Flexure Stress at Short Term Fracture (psi)	Maximum Deflection at Fracture (in.)
#1	2240	——	——
#2	1960	3300	3.37
#3	1570	3800	3.94
#4	1200	4130	3.80
#5	970	4230	3.90
#6	810	5020	5.06
#7	000	9300	8.50

Test Conditions

Test Bars: 2 x 4 x 48 in. Plexiglas G

Moment Arm: 39 in.

Temperature: 40-105°F range during long term testing
65°F during short term testing

Location: Outdoors, exposed to direct sunshine; El Cajon, CA

Table 5. Physical and chemical properties of surface and subsurface layers in 2.5-inch Plexiglas G.

Location of Positively Stressed Specimen Surface	Flexure Test ASTM D-790			Molecular Weight		Free Monomer Percent
	Strength, psi	Modulus, psi	Type of Failure	Number Average	Weight Average	
Outward weathered surface	11,500	480,000	Brittle	378,800	665,100	0.57
0.005 inches removed from outward weathered surface	14,700	490,000	Ductile			
0.02 inches removed from outward weathered surface	15,800	480,000	Ductile	760,100	1,314,000	
0.04 inches removed from outward weathered surface	16,000	490,000	Ductile	12,140,000	1,675,000	
0.06 inches removed from outward weathered surface	16,200	490,000	Ductile	1,808,000	2,336,000	
0.08 inches removed from outward weathered surface	16,200	490,000	Ductile			
0.10 inched removed from outward weathered surface	16,100	480,000	Ductile			
Interior of the 2.5-inch thick Plexiglas G pentagon	15,800	490,000	Ductile	1,863,000	2,329,000	0.25
0.06 inches removed from inward unweathered surface	15,900	490,000	Ductile	1,514,000	1,963,000	
0.04 inched removed from inward unweathered surface	15,500	470,000	Ductile	1,096,000	1,632,000	
0.02 inches removed from inward unweathered surface	15,600	480,000	Ductile	578,000	870,900	
0.05 inches removed from inward unweathered surface	15,800	480,000	Ductile			
Inward unweathered	15,400	480,000	Brittle	437,000	683,900	0.31

NOTES:

1. The specimens were approximately 0.25 inches thick.
2. The specimens were cut from the 2.5-in thick spherical pressure hull of NEMO submersible. The submersible was commissioned in 1970 and decommissioned in 1980. The submersible was stored outdoors from 1975 to 1981.
3. Outward surface – convex exterior of NEMO hull, exposed to seawater and weathering.
   Inward surface – concave interior of NEMO hull, exposed to condensation and interior atmosphere pollutants.
   Interior – from midthickness of the hull.
4. Samples from outward layer were tested with outward surface in tension.
5. Samples from inward layer were tested with inward surface in tension.

Table 6. Flexural strength of 2.5-inch Plexiglas G—disc specimens.

	BIAXIAL FLEXURE STRENGTH	
MATERIAL	ARRANGEMENT A	ARRANGEMENT B
Interior of 10-year old weathered Plexiglas G	16,483 psi. mean 2,460 psi standard deviation 6 specimens	17,583 psi. mean 2,456 psi. standard deviation 6 specimens
Outward layer 10-year old weathered Plexiglas G	8,500 psi mean 2,236 psi. standard deviation 6 specimens	18,240 psi mean 2,043 psi. mean 6 specimens
Inward layer 10-year old weathered Plexiglas G	10,816 psi mean 2,616 psi. standard deviation 6 specimens	14,460 psi. mean 1,751 psi. standard deviation 6 specimens
Interior of 1-year old unweathered Plexiglas G	16,750 psi. mean 995 psi. standard deviation 6 specimens	16,250 psi. mean 910 psi. standard deviation 6 specimens

NOTES

1 The dimensions of disc specimens were 5 inches diameter x 0.5 inch thickness

2 The specimens were taken from the following locations in the 2.5 inch thick spherical pentagon, cut out from the 10-year old weathered pressure hull of submersible NEMO

<u>Outward Layer</u> — The <u>exterior</u> surface of the sphere served as one surface of the disc specimen

<u>Interior Body</u> — The disc specimen was cut from the mid thickness of the casting, both surfaces of the specimen were machined, sanded and polished.

<u>Inward Layer</u> — The <u>interior</u> surface of the sphere served as one surface of the disc specimen

3 <u>Arrangement A</u> — The discs from outward and inward layers are tested with original hull surfaces in tension. Discs from the interior of the casting with both machined surfaces have the tension surface selected at random

<u>Arrangement B</u> — The discs from outward and inward layers are tested with original hull surfaces in compression. Discs from the interior of the casting with both machined surfaces have the compression surface selected at random

4 The disc specimens were machined from the same spherical pentagon as ASTM specimens

Table 7. Mechanical properties of 2.5-inch Plexiglas-G—ASTM specimens.

TYPE OF MATERIAL	TENSION ASTM-D-638 Strength psi	Modulus psi	Elongation percent	COMPRESSION ASTM-D-695 Yield psi	Modulus psi	SHEAR ASTM-D-732 Strength psi	FLEXURE* ASTM-D-790 Strength psi	Modulus psi	FLEXURE** ASTM-D-790 Strength psi	Modulus psi	COMPRESIVE DEFORMATION ASTM-D-621 percent	IMPACT STRENGTH ASTM-D-256 Izod Notch ft lbs/in
Interior of	11,300	440,000	5.9	16,300	490,000	12,300	16,800	490,000	16,800	470,000	0.65	0.38
10-year old	11,200	450,000	6.0	16,400	500,000	12,000	16,900	500,000	16,600	480,000	0.55	0.37
weathered	11,300	490,000	5.2	16,300	490,000	12,500	16,900	480,000	16,900	500,000	0.58	0.27
Plexiglas G	11,100	520,000	4.3	16,400	500,000	12,500	17,000	490,000	16,700	490,000	0.54	0.39
Outward layer	9,660	460,000	3.1	15,900	500,000	11,400	9,520	510,000	18,100	480,000	0.66	0.31
10-year old	10,000	480,000	3.5	16,100	490,000	10,800	10,100	500,000	16,500	510,000	0.66	0.34
weathered	7,180	480,000	2.0	16,100	500,000	11,200	12,000	500,000	16,600	490,000	0.66	0.38
Plexiglas G	10,400	480,000	4.1	16,300	500,000	11,700	12,800	480,000	16,700	480,000	0.46	0.35
Inward layer	9,410	510,000	3.0	15,700	490,000	11,900	15,800	490,000	16,600	450,000	0.67	0.37
10-year old	9,290	520,000	2.9	15,700	470,000	12,300	15,600	480,000	15,800	460,000	0.64	0.36
weathered	9,870	480,000	3.6	15,700	480,000	12,100	15,700	480,000	16,700	450,000	0.88	0.29
Plexiglas G	8,910	530,000	2.7	15,500	480,000	11,100	14,300	470,000	16,000	420,000	0.74	0.36
Interior of	10,100	440,000	3.8	16,500	480,000	11,200	16,600	480,000	17,000	500,000	0.7	0.4
1-year old	10,600	440,000	6.3	16,700	470,000	11,900	16,500	460,000	16,800	480,000	0.7	0.38
unweathered	10,600	440,000	4.9	16,900	480,000	12,300	16,200	480,000	16,700	460,000	0.8	0.39
Plexiglas G	10,200	440,000	4.9	16,400	480,000	10,500	16,900	450,000	16,600	470,000	0.8	0.40

NOTES:

1. The specimens were approximately 0.25 inches thick, except for compression, deformation under load, and *impact strength specimens which were 0.5 inches* thick.

2. The weathered material was removed from NEMO pressure hull, commissioned in Bahamas during 1970 and decommissioned in San Antonio, Texas during 1981. From 1975 to 1981 the submersible was stored outdoors in San Antonio, Texas with the hatch closed.

3. *Flexure - the original hull surface is placed in tension; orientation of specimens from interior is at random.

   **Flexure - *the original hull surface is placed in compression; orientation of specimens from* interior is at random.

4. Outward layer - layer from the exterior of the pressure hull, exposed to seawater and weathering.

   Inward layer - layer from the interior of the pressure hull, exposed to condensation and interior atmosphere of submersible.

   Interior - layer from the mid thickness of the pressure hull.

DEFINITIONS

Flexural strength — maximum calculated flexure stress in a specimen under four-point loading per ASTM D 790 *at the moment of fracture initiation.*

Compressive strength — nominal calculated compressive stress in a specimen under normal compression loading per ASTM D 695 at the initiation of yielding.

Tensile strength — nominal calculated tensile stress in a tensile specimen under uniaxial tensile loading per ASTM D 638 at the initiation of fracture.

Shear strength — nominal calculated shear stress in a shear specimen under shear punch loading per ASTM D 732 at the initiation of fracture.

Effective strength — (same as residual or remaining strength) strength of material after being subjected to weathering or service loading.

Degradation of material — difference between strengths of material *prior to* and *after* placement in service or environmental test program.

Short-term loading — continuous increase in load until yielding or fracture occurs.

Sustained loading — constant loading which, once applied, is not varied in magnitude until termination of test program.

Creep — time-dependent increase in strain under constant magnitude of loading.

Modulus of elasticity — stress-to-strain ratio of material under short-term loading, (slope of the stress-strain graph on linear coordinates).

Effective modulus — stress to *total* strain ratio of material after a selected time duration of sustained loading (total strain is the *sum* of elastic and time dependent strains). The effective modulus is always less than the modulus of elasticity.

Creep rate — the rate at which the magnitude of creep increases with duration of sustained loading (i.e., microinches per inch per unit of time).

Modulus decay — the rate at which the effective modulus decreases with duration of sustained loading.

Short-term critical pressure (STCP) — hydrostatic pressure causing a pressure-resistant window to fail catastrophically under short-term loading.

Working pressure (WP) — maximum pressure for which the window is rated.

Design pressure (DP) — magnitude of pressure used in structural calculations for windows. As a rule, P equals or exceeds WP.

Conversion factor (CF) — ratio of short-term critical pressure for a brand new window to the working pressure specified by ANSI/ASME PVHO-safety standard.

Safety factor — ratio of *effective material strength* after placement of acrylic structure in service to the design stress for that structure.

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