MECHANICAL FASTENING OF SINGLE-PLY ROOF MEMBRANES INTO STEEL DECKS—AN ENGINEERING EVALUATION

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Mechanically fastened roof systems are now available from many manufacturers and appear to be the fastest growing of all application methods. There are many variations in installation techniques and new approaches to installation are developed frequently. This paper will examine some of the methods currently used for mechanically fastening roofing membranes and some of the design considerations which must be addressed when such a system is contemplated. It is our intention to explain why some systems work and others may not, and to share some of the results of years of practical research into the various methods in use today.

A mechanically attached membrane must exhibit certain characteristics to make it suitable for such application. For example, it must be resistant to the effects of ultraviolet radiation and weather, because it will not be protected by ballast. Perhaps the greatest challenge the mechanically fastened assembly faces is to resist the wind forces which act upon it 24 hours a day.

As wind currents strike the wall of a building, they are deflected from their course and gather speed in order to travel the distance required to bypass the obstruction. The increase in velocity reduces the pressure above the top surface of the obstruction to less than that on the side. The differential between this reduced pressure above the top surface and the normal air pressure under the membrane creates the phenomenon of wind uplift.

The degree of pressure differential and the resulting wind uplift force are influenced by a number of factors. The shape and dimensions of the building affect the velocity of the wind currents as they travel over it. A tall, rectangular building produces a greater pressure differential than a low barrel-shaped one. The angle at which the wind current strikes the building and its force also are important. Further, because building interiors are not airtight an interior overpressure, such as that created by air conditioning systems or a large open door facing the wind as in an airplane hangar, increases the pressure differential on the roof surface, adding to the wind uplift force.

On roof areas which are flat or gently sloped, wind currents striking at an oblique angle produce different uplift forces across the surface of the roof. The forces are greatest at the building edges, and decrease from the edge to the interior of the roof surface. Wind currents usually are variable, both in direction and force. These variations produce pulsating dynamic loads on the surfaces of the building and its structural components. The design of the structure, and specifically the design of the roof system, must accommodate these dynamic loads.

Fastening systems for single-ply roofing generally can be classified as either spot- or linear-affixed, and either penetrating or non-penetrating with respect to the membrane. One of the critical performance variables is the ability of the fastener to resist being pulled out from the deck.

In spot-affixed systems, the fastening element usually consists of a supporting plate and a fastening screw. The fastening plate can be installed on top of the roofing membrane (penetrating) or underneath it (non-penetrating). When the plate is installed on top of the membrane, the membrane is forced down by the plate which is tightly secured into the substrate by the fastener. Because the membrane is perforated by the fastener, it must be made watertight by one of the following methods: covering the fastener with a piece of membrane material which is then joined to the roofing membrane *(Figure 1);* or installing the fastener at the edge of the membrane, overlapping the next membrane panel, and sealing in a waterproof manner through a field seam *(Figure 2).* Both of these methods usually result in the fasteners being arranged in rows with equally spaced intervals so that the uplift force on each fastener is presumed to be equal.

When the fasteners are placed below the roofing membrane, the membrane is adhered or welded onto the plate *(Figure 3),* or onto a prepared membrane disc placed under the plate. The fasteners typically are equally spaced so that the uplift force on each fastener is again presumed to be equal. All of these arrangements, however, are only statically balanced. In spot-affixed systems each individual fastener is isolated in its own roof area and is exposed to the pulling forces occurring in the roofing membrane that surrounds it. These forces work on the fasteners from all sides due to varying wind directions and eventually could affect the security of the fastener in the deck.

Two different movements can occur in the fastener when it is exposed to dynamic and multidirectional wind forces, rotation and rocking. Either can cause a fastener to back out, with the following possible effects:

- a reduction in the pullout resistance of the fastener;
- an opening between the fastener head and the plate (In such cases, a sudden stress on the plate can drive it up against the underside of the screw head, causing an abrupt loading of the fastener at its anchor in the steel deck.);
- puncturing the membrane by the protruding fastener head as a result of foot traffic or the weight of snow or ice;
- forcing the fastener head downward at an angle when it or the fastener plate is depressed (This causes a relatively large rocking motion of the fastener when the roofing membrane is under tensile force, enlarging the hole in the steel deck and significantly decreasing the pullout resistance of the fastener);

- also, the portion of the fastener that penetrates the thermal insulation is subjected to forces transmitted by the steel deck, which oscillates because of wind pressure and various other dynamic and static loads. (The resulting rocking movement of the fastener further enlarges the hole in the steel deck.)

When the fasteners are arranged in the overlap area of the membrane the seam is exposed to peel stress, and the fasteners are exposed to an uneven pull under uplift force. This pull does not occur at right angles to the seam. Instead, it varies according to the distance between fasteners in a row, the distance between rows, and the differences in tensile stress in the roofing membrane resulting from the variations in uplift forces and the oscillation of the steel deck. Thus, the direction of the pull on the fasteners varies in relation to the direction of the seam, and cannot be calculated or accurately anticipated *(Figure 4)*.

Furthermore, if a fastener in the overlap works loose, the membrane is no longer held in firm contact with the substrate. Depending on the compressive strength of the insulation and the stiffness of the plate, a gap between the plate and the membrane may develop. When this happens, the membrane is held only by the screw shaft and is exposed to tearing due to the uneven pull *(Figure 5)*.

In spot-affixed penetrating systems the strength of the fastening plate must also be considered, specifically its resistance to deflection when the membrane lying immediately under it lifts and arches under wind uplift force. Plates which are too weak will deform, and the membrane can be damaged mechanically when exposed to traffic, snow, or ice *(Figure 6)*.

In spot-affixed, non-penetrating systems, when the fastener is placed under the roofing membrane, the adhesion between the plate and the membrane is difficult to verify because the membrane conceals the plate from view. If the connection is poor, the membrane is likely to peel, exposing the plate of the fastener to possible deformation *(Figure 7)*. When a membrane disc is used instead of a plate, the bond between the roof membrane and the membrane disc is under shear stress. In this case, the plate still is exposed to deformation and the membrane is again exposed to possible mechanical damage *(Figure 8)*.

The linear attached system is an alternative to spot-affixed systems. It typically consists of a fastener and a perforated bar of metal or other material. There are many different types and configurations of fastening bars available, ranging from flat strips or coil stock to U-shaped roll-formed profiles. Fastener bars can be installed in the lap area, where they are concealed by the next overlapping sheet, or in the field of the membrane, where they are covered by strips of membrane which then are sealed in a watertight fashion to the membrane on both sides of the bar.

The function of the bars is to uniformly distribute the stresses which occur along their length, thereby preventing stresses from concentrating at individual points, as in spot-affixed systems. The ability of a particular bar to act as a restraint against uplift forces depends on a number of factors: stiffness, strength, torsion resistance, and corrosion resistance. These factors are influenced by the thickness, weight, shape, and composition of the bars. The uplift resistance of the system depends on the fastening pattern.

Through the use of a bar system (cross section as shown in Figure 9) which is overlaid as a grid throughout the field of the roof, independent of the membrane layout, the roof surface is divided into small, discrete sections. The individual areas are relatively narrow and separated from each other by the bars. Because these bars are not in an overlap, as shown in Figure 5, this results in an equal upward pull on both sides of the bar simultaneously, and only at a right angle to it. The fasteners within the bars are stabilized in position because they are captive within the holes in the bar. They are also, then, ideally stressed perpendicular to the anchoring surface. The roofing membrane is thus exposed to pull at a right angle to the bar axis. Even if a screw is missing, the vertical pressure on the bars is distributed to the adjoining screws in such a manner that they are still stressed perpendicular to the anchoring surface. Even oscillation of the steel deck and thrusting movement of the insulation boards will not deflect the fasteners from their perpendicular positions because they are clamped firmly in place.

The shape of the bar is an important factor. The more the bar resists movement, the greater the allowable distance between fasteners. Consider the difference in strength and degree of clamping effect between a flat lightweight strap and a tube formed from the same metal. The tube has greater torsional resistance and stiffness, and therefore, greater strength.

The mass of the fastening element should be distributed to maximize the moment of inertia of the cross section and, thus, the bending moment. When the mass is perforated, the cross section of the bar must have a large enough moment of inertia, especially in the area of the holes, to provide the required strength and clamping effect. Consider the security that a heavy-gauge channel with hemmed sides provides when compared to that of a simple flat strip. And, if the bars are designed to permit spacing independent of the roof membrane width, then the screw spacing can be increased as the distance between bars decreases. Conversely, screw spacing must be decreased as the distance between bars increases. The fastening pattern of the screws within the bar can be mathematically calculated to resist the existing uplift forces for a given bar spacing. The redundancy of the system is such that the uplift resistance is shared by the screws, and the system can be designed to accommodate the dynamic forces resulting from wind and deck movement.

Corrosion resistance of the bars is also critical, particularly in lap fastened assemblies. If moisture is present in the lap areas, as a result of condensation within the insulation or vapor from the building interior, the metal fastening strip and each individual screw is vulnerable. Only corrosion resistant materials such as galvanized or stainless steel strips should be used. In lap-fastened systems, the underside of the overlap area cannot be protected from moisture by caulking such as is typically used on the outside surface of rubber joints. Therefore, this area is of particular concern. The corrosion resistance of the screws will be discussed later in this paper.

Testing was conducted to compare the uplift resistance of several different systems. The dynamic loading of the test system simulated actual field conditions. Five assemblies were constructed in a 3- × 3-meter (10- × 10-foot) test panel, over a 75mm (22 gauge) steel deck, with a loosely laid

1.2mm (48-mil) fiberglass-reinforced PVC membrane *(Figure 10).*

Test panel #1 consisted of the membrane spot fastened with an expanding hollow dowel (Hardo-type fastener) and 80mm diameter round plates, at a fastener density of 3 per square meter.

Test panel #2 consisted of the membrane spot fastened with a 4.8mm (.188-inch) diameter self-drilling screw and a 80 × 80mm (3- × 3-inch) quadrangular plate, at a rate of 3 per square meter.

Test panel #3 consisted of the same elements as #1, but with four fasteners per square meter.

Test panel #4 consisted of the same elements as #2, but with four fasteners per square meter.

Test panel #5 consisted of a 14-gauge galvanized steel, linear fastening bar with U-shaped profile secured with four 4.8mm (.188-inch) diameter self-drilling screws per meter. Distance between bars was 1.35m (4.5 feet).

The panels were subjected to compressed air introduced between the steel deck and the roofing membrane. The dynamic load was simulated by pulsing the air at a rate of 8 to 9 pulsations per minute. Air pressure was controlled and varied, beginning at 500 Pa (10 psf), and increased daily in increments of 500 Pa (10 psf). The results are shown in Table 1.

Examination of the results indicate the following:

Test panels #1-4 demonstrated an average dynamic pull out resistance of approximately 850N (187 pounds) per fastener. This represents approximately 50 percent of the static pull-out values typically reported by fastener manufacturers. Test panel #5 resulted in a pull-out value of 1000N (220 pounds) per fastener.

The plate and screw assemblies used in test panels #2 and #4 failed under the test conditions at a very minimal load. The plates were severely and permanently deformed. In order to stay within the limits of permanent deformation, the loads could not exceed 450N (100 pounds) per fastener for sample #2, and 600N (132 pounds) per fastener for sample #4. These values also vary according to the shape of the plate.

The conclusion is that the dynamic pull out values of the fasteners, not the static values, must be used as the basis for the design of mechanically fastened membrane systems, with an appropriate factor of safety. Furthermore, the uplift resistance of the system varies with the spacing between fastening elements. It is not practical to specify a standardized fastening pattern to be used in all applications when the demands of buildings and their environments vary. The concept of designing for each particular installation has been used successfully in practice for a number of years, but it requires knowledge of the mathematical formulae needed to perform the calculations which determine the appropriate fastening pattern. Such an approach precludes the use of the lap-fastened method because there is no way to vary the spacing of the bars since it is determined by the width of the sheets.

The fastener bars must be arranged perpendicular to the corrugation of the steel deck so that the resulting linear load is distributed across the deck and not concentrated on any individual corrugation, or on any individual supporting structural beam. This assures that wind uplift forces are transmitted over the whole deck surface. The bars are not exposed to stress due to normal deflection, and actually have a stiffening effect on the deck. It is even possible that the added stiffness from the bars decreases the oscillation of the deck, depending upon the distance between bars. In a recent experience, when the bars were attached with multiple fasteners in one corrugation, the pull out strength of each fastener was up to 35 percent less than when using a single fastener per corrugation. This value depends on the type of fastener and the gauge of the steel deck. In any system, an even spacing of fasteners is important since random spacing or accidental pattern variation in pattern can produce an increase in the uplift load.

Fasteners penetrating from the exterior to the interior, function as cold bridges. As they are most often made of steel, they are good thermal conductors. Therefore, it is important to know the temperature conditions where the fastener enters the steel deck. During the winter, the temperature of the fastener in this area should not be allowed to fall below the dew point temperature of the interior air, because this would cause the perforated steel deck, unprotected at the screw hole, to rust. Over a long period of time, rusting results in a decrease in fastener pull-out resistance. Whenever the temperature at the screw hole is lower than the dew point, there will be condensation.

Testing was conducted to observe the temperature of the fastener at the point of penetration through the steel deck. The tests involved varying the interior temperatures, exterior temperatures, insulation thickness and R-values. The results of one test where the interior temperature was 20C and the dew point is 18C are shown for four insulation thicknesses in Figure 11. The following conclusions can be drawn:

1. The temperature at the point of perforation can only be increased by raising the R-value of the thermal insulation.
2. As expected, fasteners made of steel are better conductors of cold temperatures than fasteners made of synthetic materials.
3. The portion of the fastener which projects under the deck is not an effective conductor of the warm interior air.

For these reasons it is advisable to determine the temperature at the point of perforation for each individual project.

Corrosion is another major concern when using steel fasteners. The likelihood of rust formation depends on the humidity present between the vapor retarder and the membrane. As humidity increases, so does the risk of rusting.

Therefore, it is of great importance that the thermal insulation be installed dry, and that whatever condensation occurs within the insulation during the winter dries out during the summer. The only way to assure this is to place a vapor retarder between the steel deck and the insulation. The vapor retarder also inhibits the exchange of air between the interior and the air contained within the insulation layer. Without a vapor retarder, when the membrane billows from wind uplift the space created is rapidly filled by interior room air flowing through the joints between insulation boards and the joints of the steel deck. The warm air immediately condenses upon meeting cold exterior air. Thus the vapor barrier also serves as an air-flow barrier, and is doubly important.

Corrosion of fasteners also is influenced by the composition of the thermal insulation. Tests conducted with different fasteners and different insulation boards showed the following results:

- as the air temperature increased with constant relative humidity, corrosion increased.
- when all temperature and relative humidity conditions were the same, the different insulation materials showed the following degrees of corrosion promotion:

Slight Corrosion	Medium Corrosion	Strong Corrosion
Expanded Polystyrene	Polyurethane Isocyanurate Rockwool Perlite	Phenolic Foam

An absolute ranking of these materials requires further study, and the effect varies from one manufacturer to another. Also, a combination of variables appear to influence the corrosion promotion. For example, it appears that with polyurethane, corrosion promotion increases as the fire resistance of the material is improved. The important point is that only corrosion-resistant fasteners should be used. In the case of reroofing, it is advisable to use stainless steel or other highly corrosion resistant fasteners because of the residual moisture in the underlying roof system.

Perhaps the most important component of any mechanically fastened roofing assembly is the membrane itself. It must withstand not only the effects of weather, but it also must have the mechanical strength to resist the tensile stresses resulting from uplift forces. The ability of the membrane to maintain its strength over its service life is critical to the longevity of the roof system. The success of any mechanically fastened system depends on the membrane's ability to resist wind uplift forces and to transfer these forces into the construction substrate through suitable fastening elements. Any decrease in the membrane's mechanical strength over time will compromise its ability to withstand and transfer uplift forces.

Variations in uplift force cause the roofing membrane to lift and arch between the fastening elements and then to fall back. The height of the arch depends on the amount of uplift force, the distance between fasteners, and the stress-strain characteristics of the membrane. The elasticity of single-ply membranes is far greater than that of conventional materials; therefore, the amount of displacement resulting from wind uplift also is far greater.

The elastic limit of the material, the maximum stress which can be accommodated before permanent deformation occurs, should not be exceeded. This means that each time the roofing membrane lifts off the deck it must return to its original dimensions. Tensile stress to which the membrane will be subjected should be limited by design so that it will not exceed, by a reasonable factor of safety, the elastic limit. Therefore, it is important that the designer have precise knowledge of the mechanical properties of the membrane, both as manufactured and especially after it has been exposed to the atmosphere. Some of this information can be gained only through actual long-term experience with the material used in a mechanically fastened roof assembly.

Materials which are subject to cold flow, or creep, especially under elevated temperatures, are not suitable for mechanical fastening. Neither are materials whose stress-strain characteristics change during long-term aging, because the elastic characteristics also change. The same is true of materials whose elasticity is affected by heat or humidity.

Laminated products are especially at risk in the overlap area. If the reinforcing scrim reaches the edge of the sheet, it is difficult to achievega perfect seam. It the scrim stops short of the seam width, then the joint area without scrim has a significantly different stress-expansion behavior than the rest of the sheet. Membranes which are subject to cold flow will deform in the joint area where there is no scrim. These deformations will tear over the long-term.

Therefore, all membranes which are to be used for a mechanically fastened system should be subjected to seam strength tests to verify that the material breaks alongside the seam, even when exposed to elevated temperatures. For this application method, the seam must be stronger than the material itself.

The permissible extension of the membrane must be selected by the system designer. In all cases, it must be lower than the elastic limit of the reinforcement. Only reinforced membranes should be used because the mechanical strength and the waterproofing feature are provided separately: strength by the reinforcement; waterproofing by the membrane material. The use of reinforcement which has a much lower elastic limit than the elastomeric or thermoplastic membrane limits the amount of extension which the sheet can endure when exposed to the dynamic stresses of the wind. A non-reinforced sheet undergoes demonstratable, but not predictable, changes in physical properties. These changes result from atmospheric exposure and vary from location to location. The reinforcing material, suitably waterproofed by the membrane, shows much greater stability over its full service life.

Years of research and practical experience emphasizes that a successful mechanically fastened roofing system should consist of the following components:

- a vapor retarder, which also serves as an air barrier;
- insulation which is dry and does not promote the corrosion of fasteners which penetrate it;
- a reinforced roofing membrane which exhibits the requisite features of waterproofing integrity, mechanical strength, a known elastic limit, and the ability to retain all of these properties throughout its service life;
- seams which are stronger than the membrane material itself;
- a linear fastening profile, spaced at intervals designed specifically to accommodate the individual requirements of the application, including building geometry and wind uplift as well as other dynamic forces;
- corrosion resistant fasteners spaced at intervals specifically designed to provide the required wind uplift resistance.

Any compromise in any of these elements should be carefully considered based on the type of material and the other components of the system. Because of the wide range of materials available in single-ply systems, each must be considered on its own merits and material properties.

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TEST PANEL NUMBER	FASTENING METHOD	FASTENER SPACING	PRESSURE AT FAILURE	NUMBER OF PULSATIONS	RESULT
1	SPOT FASTENED A	3/m²	1000 Pa 20 psf	6,800	PULLING OUT OF PLATES
2	SPOT FASTENED B	3/m²	1500 Pa 30 psf	8,000	PERMANENT DEFORMATION OF PLATE
			2500 Pa 50 psf	17,000	PULLING OUT OF SCREWS
3	SPOT FASTENED A	4/m²	2500 Pa 50 psf	16,000	PULLING OUT OF PLATES
4	SPOT FASTENED B	4/m²	2500 Pa 50 psf	16,000	PERMANENT DEFORMATION OF PLATE
			3500	24,000	PULLING OUT OF PLATES
5	LINEAR	4/m	2500 Pa 50 psf	19,000	AT PERIMETER ONE SCREW HEAD BROKEN OFF, TWO SCREWS PULLED OUT FROM STEEL DECK
			3000 Pa 60 psf	22,000	AT MIDFIELD STRIP SCREWS PULLED OUT FROM DECK

A = ROUND PLASTIC PLATE WITH INTEGRAL EXPANDING ANCHOR
B = SQUARE METAL PLATE WITH SELF DRILLING SCREW

Table 1

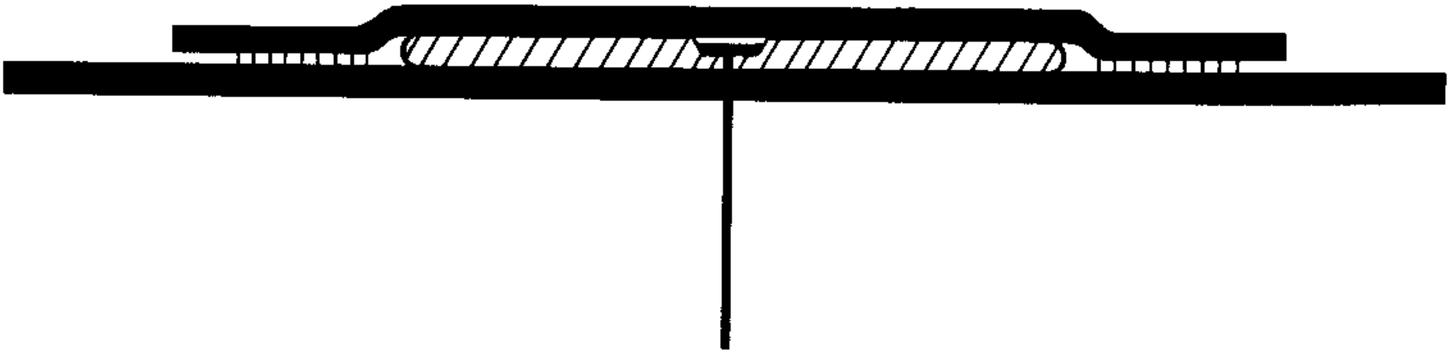

Figure 1

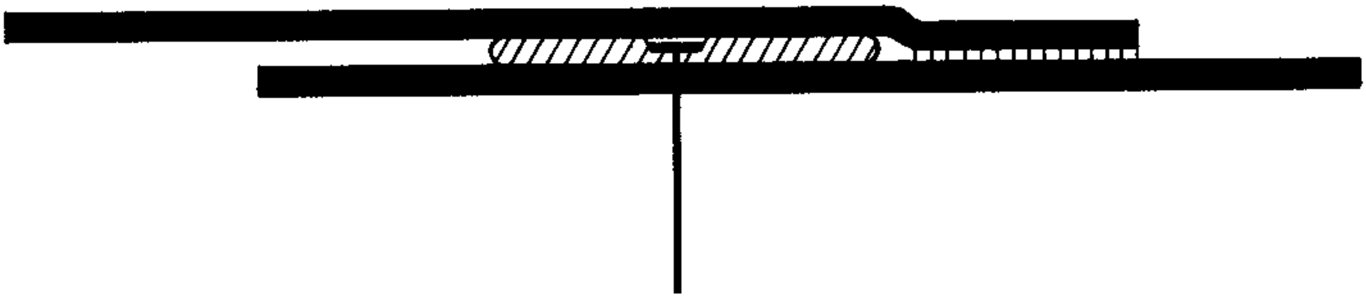

Figure 2

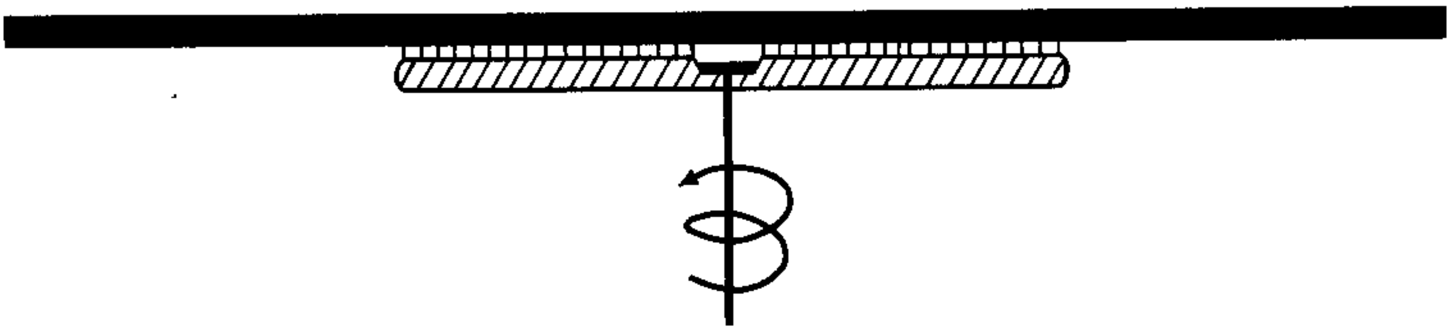

Figure 3

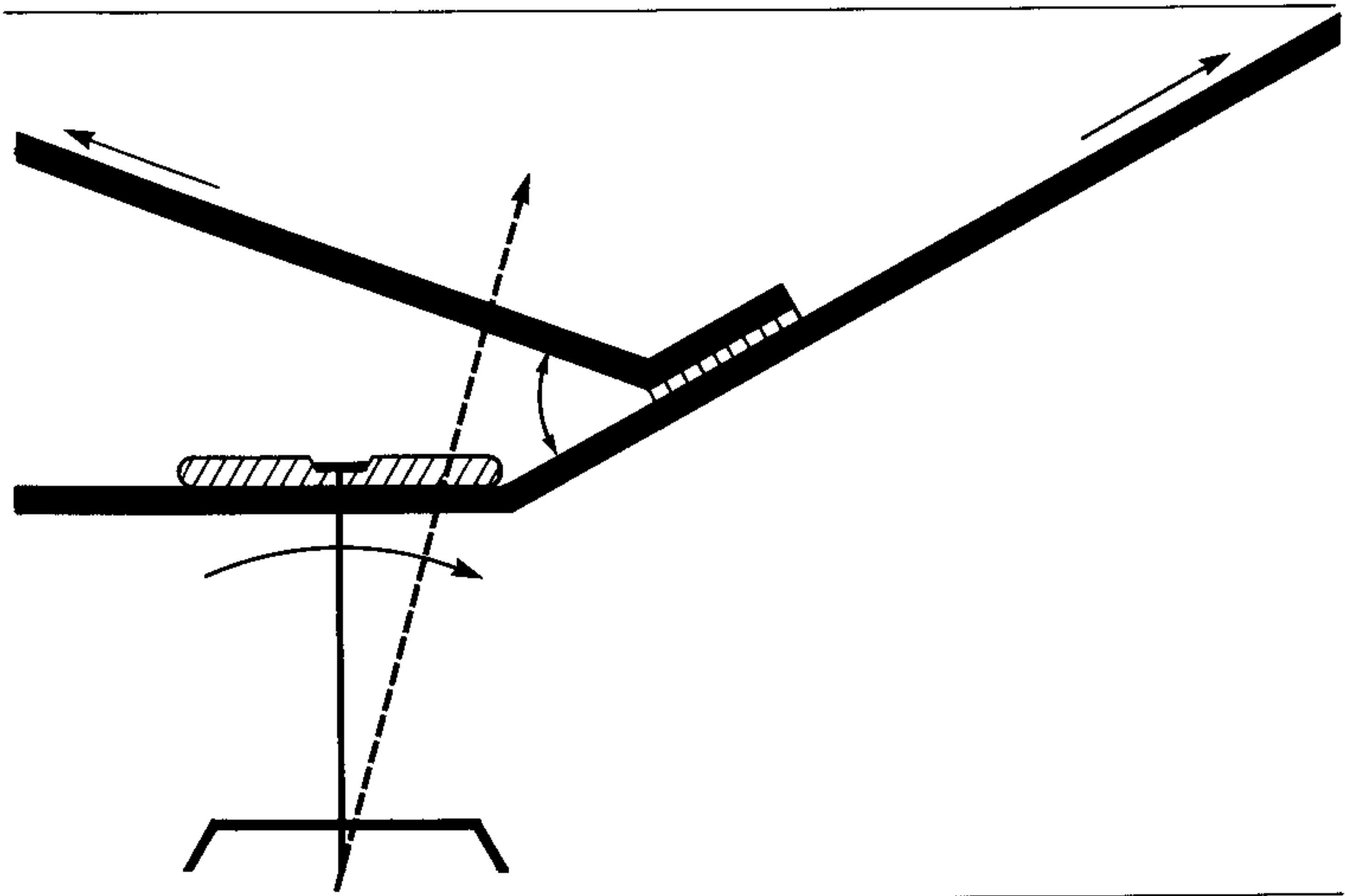

Figure 4

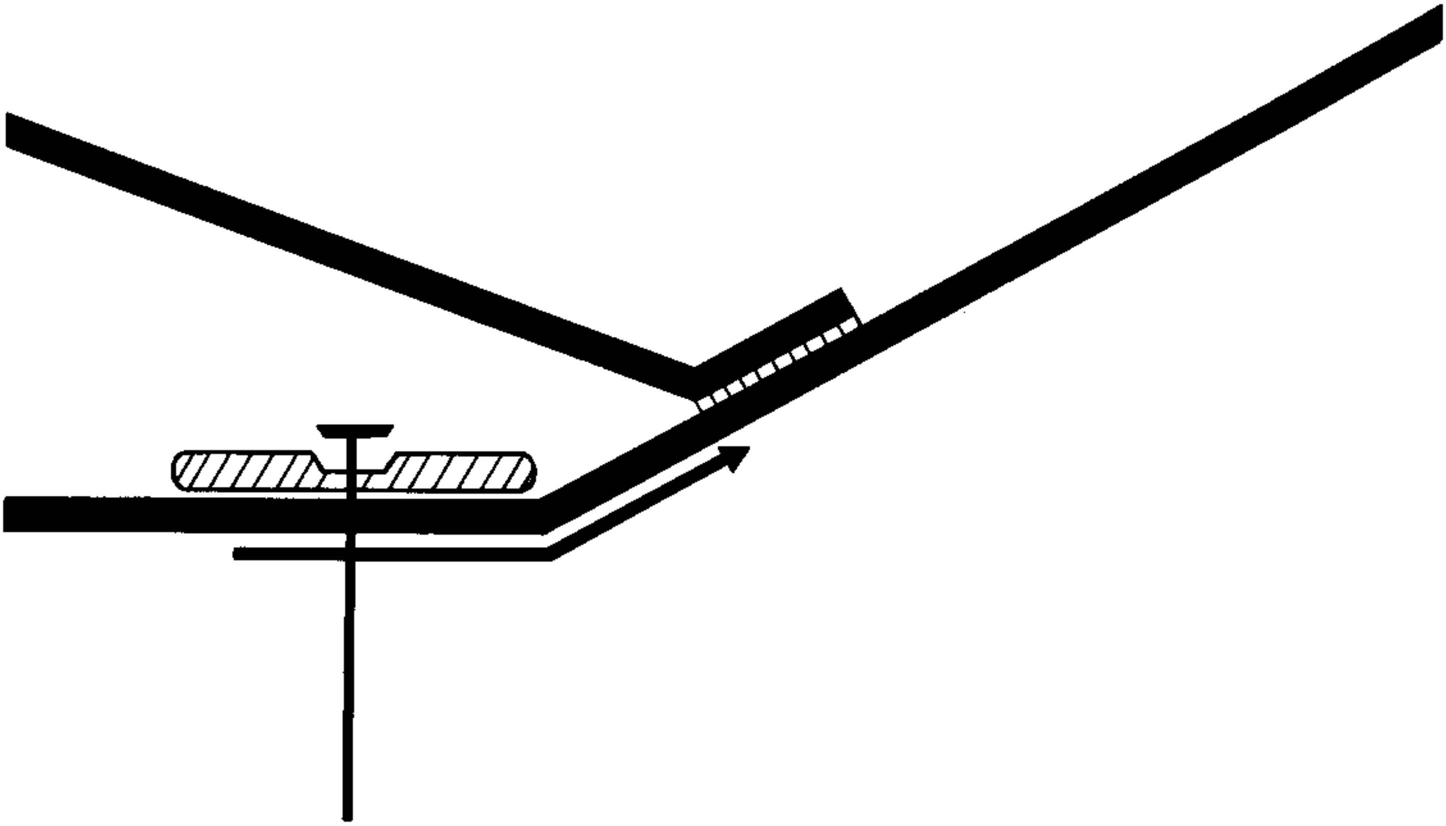

Figure 5

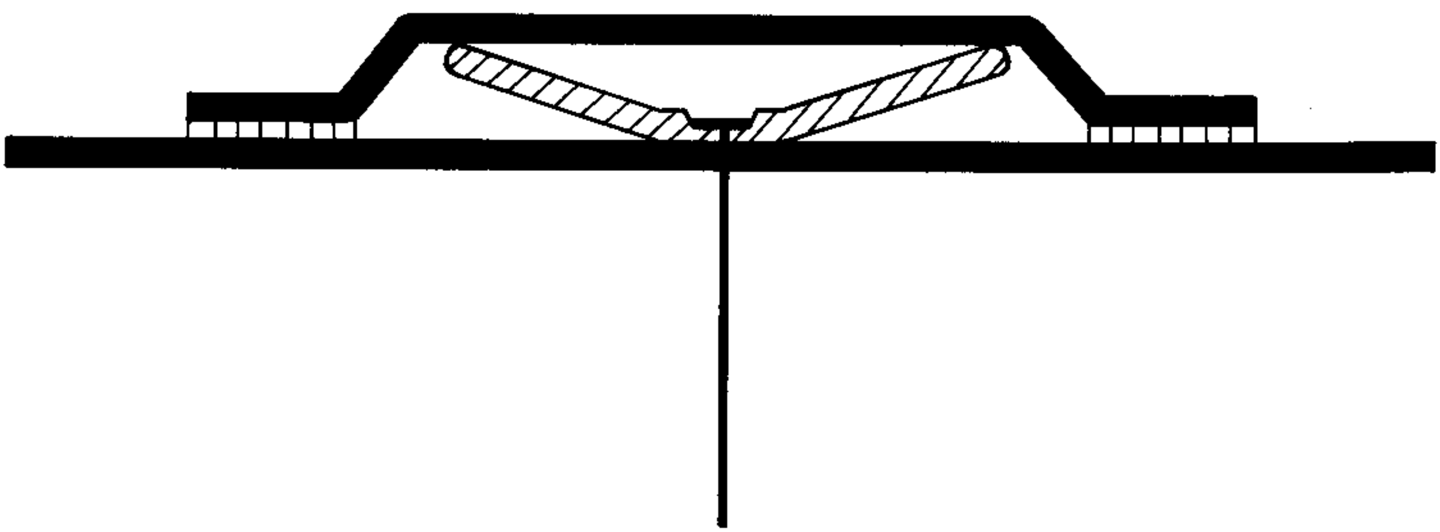

Figure 6

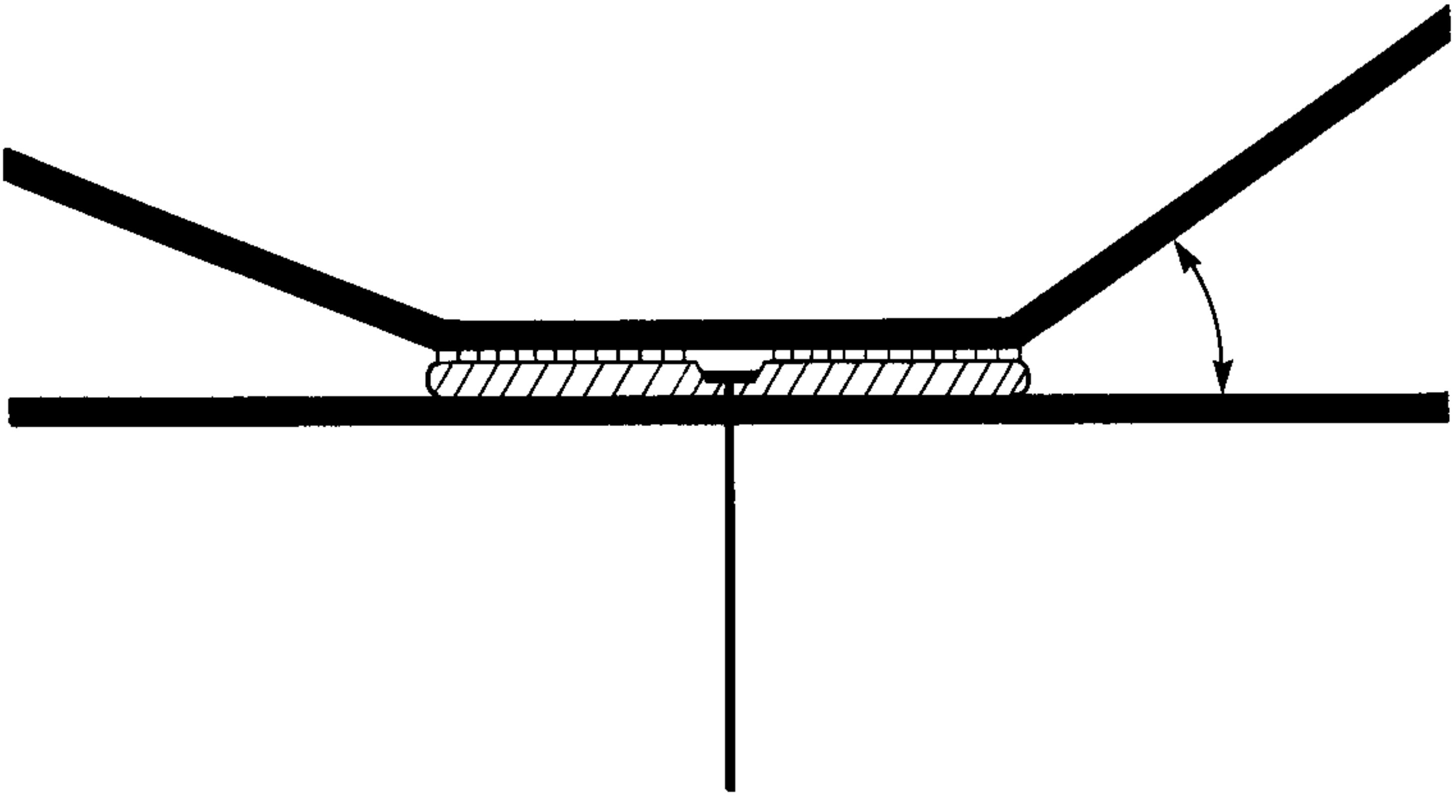

Figure 7

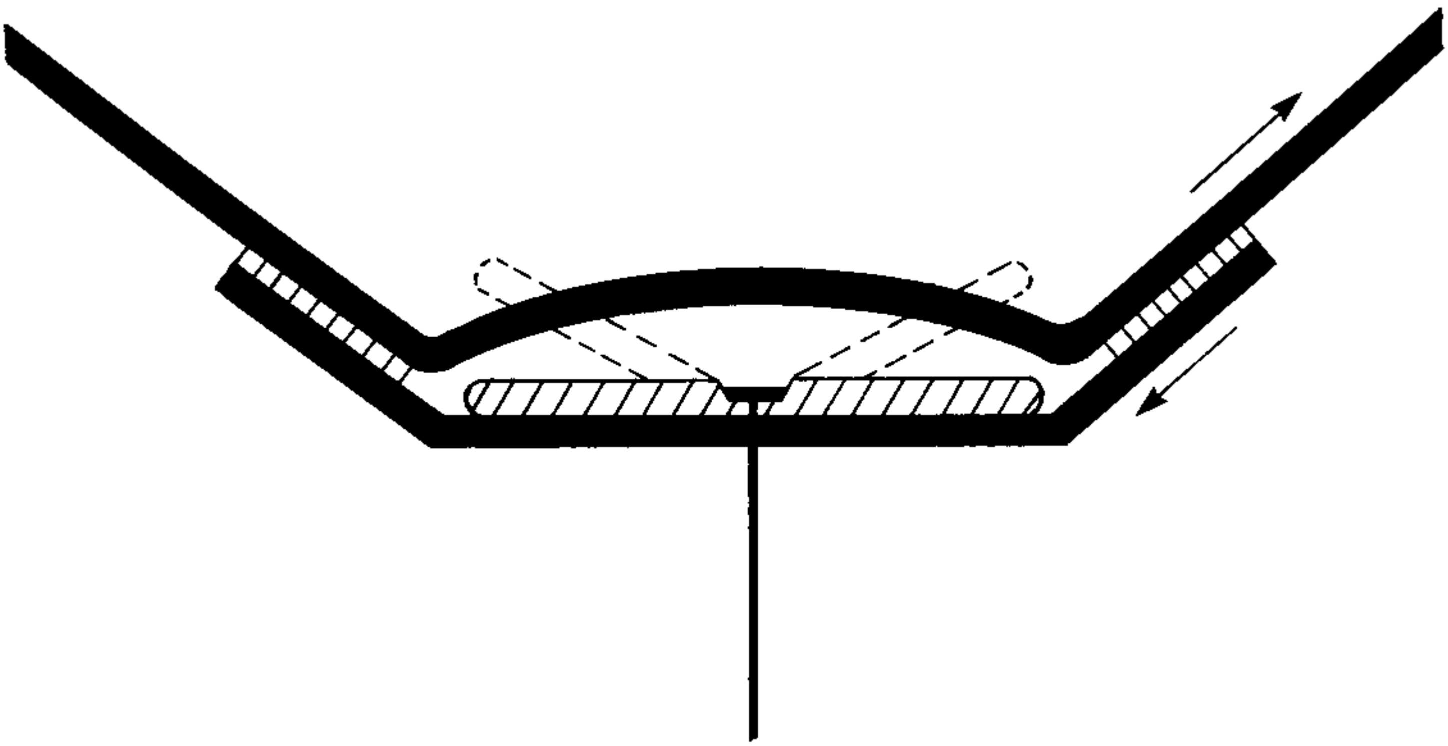

Figure 8

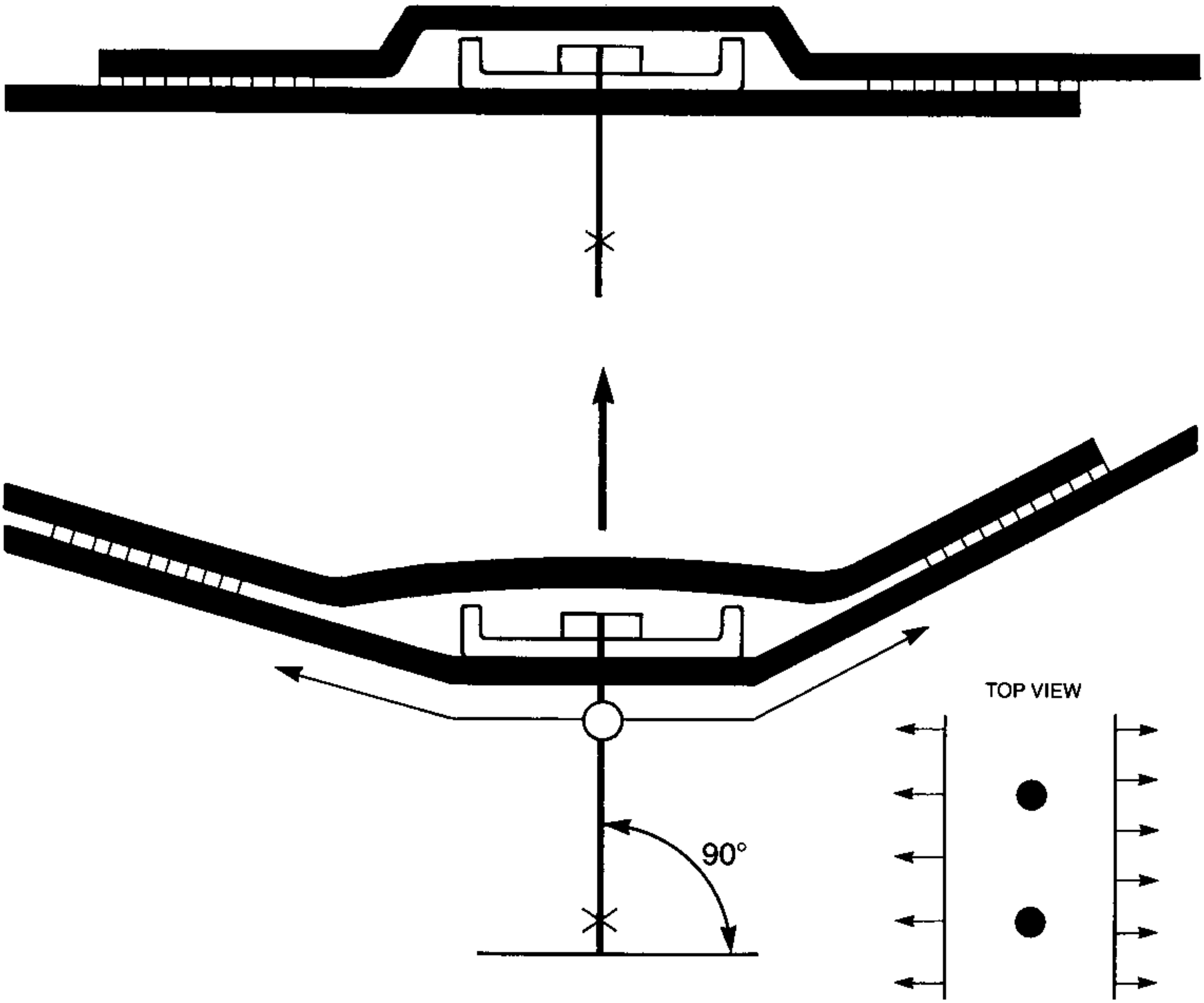

Figure 9

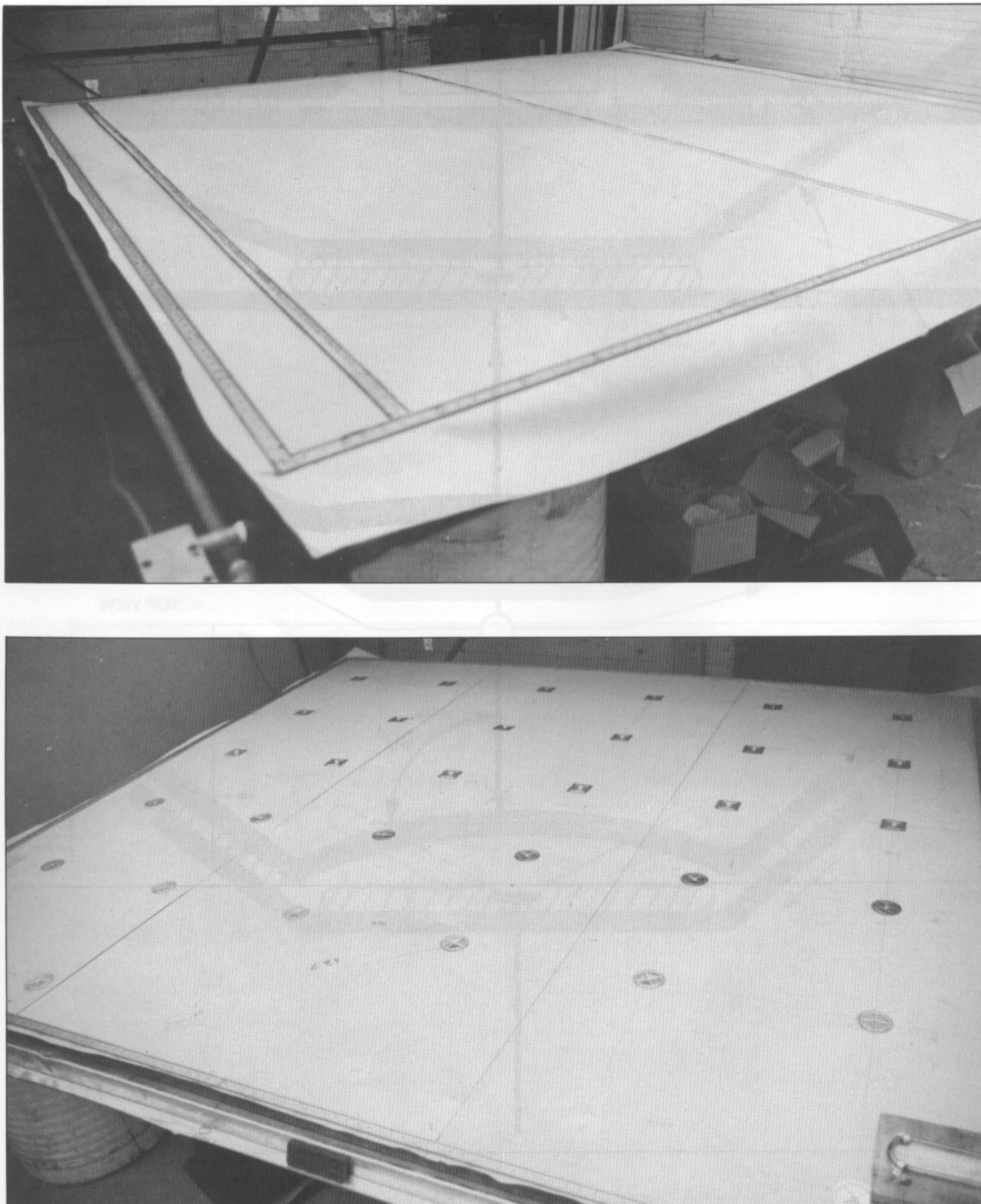

Figure 10

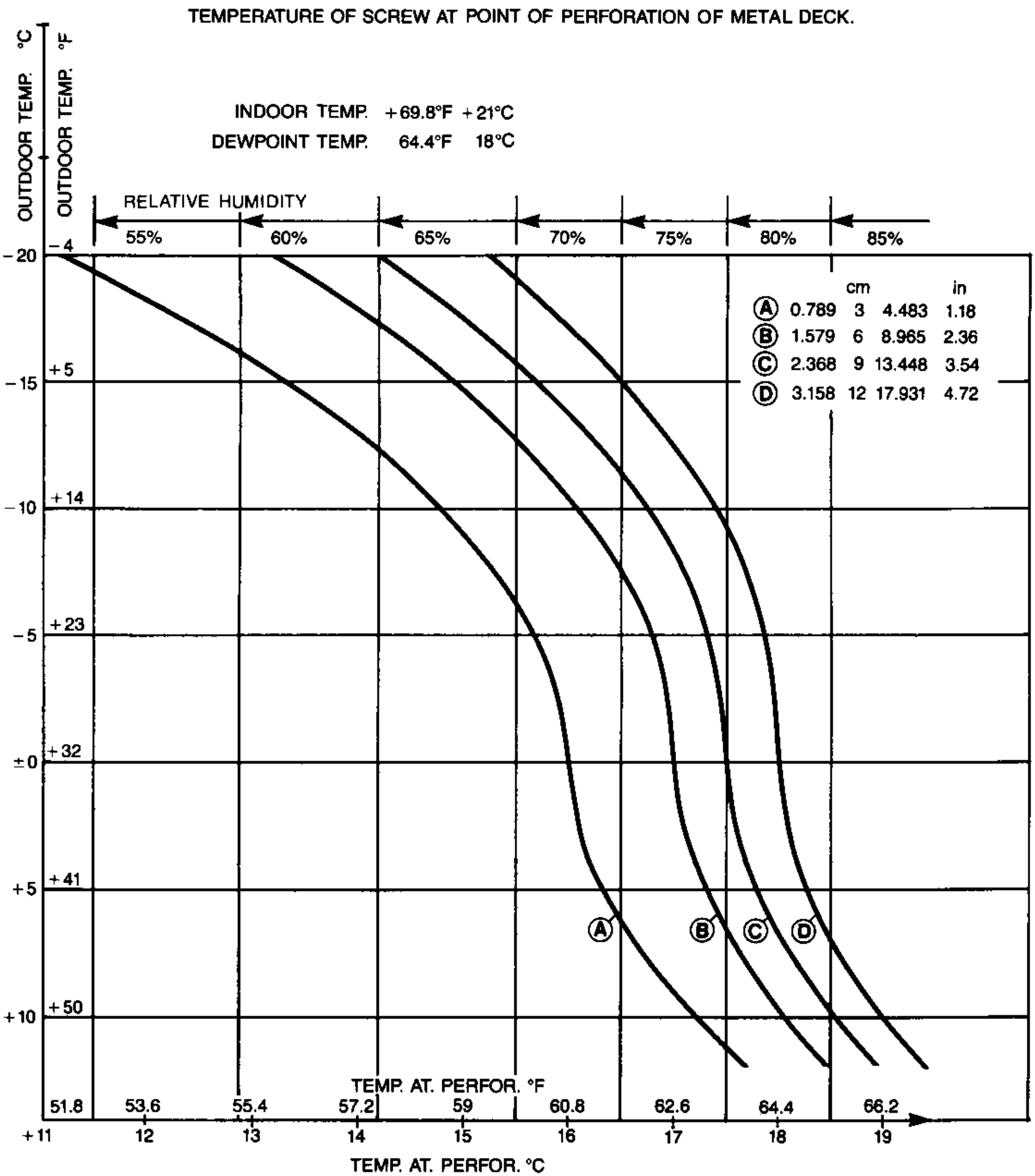
TEMPERATURE OF SCREW AT POINT OF PERFORATION OF METAL DECK.
INDOOR TEMP. +69.8°F +21°C
DEWPOINT TEMP. 64.4°F 18°C
OUTDOOR TEMP. °C
OUTDOOR TEMP. °F
RELATIVE HUMIDITY
55% 60% 65% 70% 75% 80% 85%
cm in
Ⓐ 0.789 3 4.483 1.18
Ⓑ 1.579 6 8.965 2.36
Ⓒ 2.368 9 13.448 3.54
Ⓓ 3.158 12 17.931 4.72
−20 −15 −10 −5 ±0 +5 +10
−4 +5 +14 +23 +32 +41 +50
Ⓐ Ⓑ Ⓒ Ⓓ
TEMP. AT. PERFOR. °F
51.8 53.6 55.4 57.2 59 60.8 62.6 64.4 66.2
+11 12 13 14 15 16 17 18 19
TEMP. AT. PERFOR. °C

Figure 11