PERFORMANCE OF FASTENERS

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Fasteners play an important role in our lives. Fasteners keep the car wheel intact at high speeds. They keep the airplane frame and body encapsulated under high winds. It's hard to find anything in our surroundings that does not employ fasteners. Some products use only a few; some use many. Each jumbo jet uses 2.5 million fasteners at a cost of 1.5 million.[1] Types and shapes of fasteners may vary from one application to another, but the purpose remains the same: the joining of pieces or multiple layers.

Fasteners also keep many roofs intact. Although many attachments are impossible without fasteners, in roofing, options are available. Most roofing fasteners are threaded, but vary by type. More and more threaded fasteners are being specified in roofing applications.

ROOFING FASTENERS

Threaded roofing fasteners were introduced to the roofing market by a Chicago firm in 1973; screw and plate systems provided additional holding strength for some of the older systems. Contractors liked these systems because of their ease of application. Prior to this, spot-fastening with asphalt and cold-applied adhesive systems were used. These methods of weak attachment decreased the risk of fire, but increased the potential for blow-off. Factory Mutual statistics have indicated that during the 10-year period of 1971-1980 there were 1,247 windstorm losses to steel-deck roofs, totaling $83.6 million.[2]

Finally, recognition of mechanical attachment systems came from Factory Mutual in May 1983 when it was announced in Factory Mutual Loss Prevention Data Sheet 1-28 that mechanical fastening was the only recommended method of attaching rigid insulation board to metal deck.[3] Factory Mutual developed an apparatus to test mechanical fastening systems subject to simulated wind uplift loads. Two classifications of wind storm protections were set up, 1-60 and 1-90.

Wind damage to a roof could depend on the ability of the fastening system to withstand these rated loads. Each component of the roofing system-fastener assembly, deck, insulation and membrane—experience some load. Each component in the assembly plays an important role in keeping the entire mechanical fastening system secured. These fastener characteristics can affect the fastening system's performance:

- Drill point
- Thread design
- Stress plate and fastener head
- Fastener backout vs. pop up
- Corrosion
- Application guidelines.

DRILL POINT

The drill point is a sharp, pointed surface at the bottom end of the fastener. It is used to drill a pilot hole into a steel deck for threads to follow. A threaded fastener that drills holes is called a self-drilling fastener.

There are many kinds of self-drilling fasteners available. This type of fastener drills and taps the roof deck in one operation. Drilling efficiency is important, because the time required to drill is a cost factor. A concentric drill point combined with an efficient thread design provides greater pullout strength, higher stripping torque and lower tapping torque.

THREAD DESIGN

Thread design is a critical feature of a threaded fastener. An efficiently designed thread will provide maximum pullout with minimum driving torque. The difference in area between outside diameter minus root diameter of the thread and top slope of the thread angle are the factors responsible for pullout force (Fig. 1). Thread design with lower top slope of included thread angle and self-drilling point concentric to mean thread diameter reduces backout and provides much higher stripping torque. This will eliminate the possibility of fastener stripout during installation.

STRESS PLATE AND FASTENER HEAD DESIGN

The head of a fastener in combination with the stress plate provides clamping force to the assembly. The stress plate gives rigidity to the assembly and maintains preload tension in the fastener. Stress plates are made of either metal or plastic. Metal plates are susceptible to corrosion while plastic plates are susceptible to excessive creep if not properly designed. Both metal and plastic plate performance depend on the ability to resist deformation under various types of stress-loading conditions.

There are many design factors affecting roof fastener assemblies. When a strong connection between screw and metal deck is required, a preload (50 to 60 percent of strip torque of a fastener) is selected to place the parts in compression for better resistance of external tensile load and to create friction between parts to resist shear load. The importance of preloading the screw cannot be underestimated because a high preload improves both the fatigue and resistance to backout. The creep or rigidity component of insulation should be considered to avoid loss of preload. Low density or less rigid insulations may require higher strength board overlay to keep preload constant.

The tension load in a fastener assembly, which is subjected to a fatigue action, should be carefully analyzed. A life cycle test of fastener assembly in the lab can provide the safe load for a particular assembly. A proper fatigue design factor for the fillet under the screw head and critical threads should be considered in order to reduce the stress in these vulnerable areas.[4]

BACKOUT VS. POP UP

A desert can be a laboratory to analyze the effect of wind. What we see resembles what happens on a roof. When wind flows over the desert, it tends to lift the sand and form sand dunes. Sand dunes are a visual resemblance to the ballooning of membrane due to wind uplift. Ripples in the sand resemble the rippling of a roof caused by fluttering of the membrane.

Wind uplift creates upward forces on fastener assemblies and shear loading. Fluttering of the membrane exerts shear load and the strength of that shear load depends on the angle of the stretched membrane. When a mechanically attached membrane is subjected to flutter, it puts fasteners under shear load. The shear load effect increases if fastener length is longer from head to deck.

FASTENER BACK-OUT

Field inspection revealed that fastener backout in the single-ply membrane attachment was caused by fluttering of the membrane. Backed out fasteners may puncture the membrane when subjected to applied load, such as roof traffic. A punctured membrane results in a leaky roof.

FASTENER POP-UP

Inspection of mechanically attached insulation to a metal deck revealed that, where the fastener head was pushing the membrane upward, fasteners were actually sticking up 1/8 inch to 1/4 inch. The common theory was that screws had backed out. Upon close inspection, the fastener had not backed out; the insulation had compressed. The compression was due to roof traffic, or in some cases, the insulation was old and had lost its compressive strength. This condition is referred to as "pop-up" (Fig. 3).

A field study of some of the single-ply roofs in Europe (Buildex, United Kingdom) produced the following observations:

a) Screws pulled out of the deck as a result of being over-driven and stripped out during installation. Evidence was found of washer deformation resulting from over-driving; examination of the steel deck suggested parts had been stripped out.

b) Screws coming loose and working themselves out of the deck. In these circumstances, the screw had worked out of the deck prior to catastrophic failure; evidence of screw-head impressions in the membrane were noted. No evidence of damage to the steel deck was observed, and good thread engagement was obtained when products were re-assembled into holes.

c) Screws pulled out of the perimeter detail resulting from incorrect installation. Because of the increased metal thickness occurring at the perimeter of roofs, some fasteners require predrilled holes in these applications. Failures were noted in this area because holes had been drilled that were oversize to such an extent that they provided a clearance on the screw thread. Testing of products within the laboratory was conducted to try to establish those areas where connection performance could be improved. Normal static testing for tensile strength, shear strength (45° angular pull), backout torque and stripping torque for connections were carried out for various screws. The results provided no clear guide as to the characteristics that affected connection performance under high wind-load conditions.

A test machine was built by a fastener manufacturer in 1985 to simulate loading conditions and determine likely performance of connections under actual wind-loading conditons. The test machine consists of a test bed designed so that test samples consisting of a roof decking sheet, insulation board and membrane could be attached to simulate actual site situations. Various loads could be achieved by adjusting air pressure and various cycling rates achieved by adjustment of the motor speed. The angle of applied load was fixed at 45° to the plane of the metal deck and insulation sheet. Rotation of the fastener was measured by marking both the screw head and plate. Any relative movement of the head marking was measured in degrees or turns. The number of cycles applied was recorded by a mechanical counter (Fig. 2).

HYPOTHESIS

The negative pressure created on the roof during high wind-loading causes varying uplift loads on the membrane at different positions on the roof surface. The uplift loads cause the membrane to rise locally and as the wind blows, a "wave" then progresses across the roof in the direction of wind flow. The result of this wave movement on the connection creates a load in a direction opposite to the wind flow as the wave approaches and then in the same direction to the wind flow as the wave passes. The resultant effect will be a connection that is first subject to full load in one direction, and then full load in the opposite direction.

TESTING OF ANTIBACK-OUT SYSTEM

Many tests were conducted to measure back-out resistance of standard and antiback-out membrane fastening systems. A test fixture shown in Fig. 2 was used to evaluate the performance. Reinforced membrane and wood-fiber insulation were mechanically attached to the metal deck. Two separate test specimens were prepared using standard fastening systems.

1. 2-inch round single-ply metal plate and 3¾-inch threaded roofing screw.
2. 2-inch round single-ply membrane plate with antibackout design and 3¾-inch threaded roofing screw.

The reinforced single-ply membrane was placed between the roofing plate and insulation to create a load on the fastening system. A linkage mechanism was designed to apply load on the fastener through the plate.

- The load was applied at 45° to simulate wind conditions.
- Two sides of the single-ply membrane were attached to a 2-inch stroke chain-linked mechanism.
- Once the tester was activated, the membrane was pulled from one side to the other, via the use of a test fixture, creating a jerking action.
- Fastener head, plate and membrane were marked with respect to each other to measure any movement.
- Cycles were measured at initial breakoff and at ultimate pullout or 2000 cycles, whichever comes first.

MATERIAL USED TO CONDUCT TEST

- Reinforced single-ply membrane approximately .035 thick.
- Wood-fiber insulation 3 inches thick.
- Intermediate rib metal deck 1R 22.030 thick.
- Single-ply membrane plate with antibackout design.
- Standard 2-inch round single-ply membrane metal plate.
- Coated 3¾-inch fastener.
- Load applied at membrane 30 pounds.

- Fastener tightened to 15 in./lbs.
- Frequency of cycle 200 cycles/minute.

RESULTS OF TESTING

Fasteners	Back-out start cycle	Complete turns	Cycles
Standard 2″ round single-ply membrane metal plate and screw	196	4.5	2000
	689	3.0	2000
	314	4.5	2000
	252	6.0	2000
	89	5.0	2000
Single-ply membrane plate with antibackout design and screw	—	0	2000
	—	Membrane failed	393
	—	0	2000
	—	0	2000
	—	0	2000

CONCLUSION

The testing carried out on existing systems resulted in the reproduction of similar failures to those which were experienced in the field. Observation revealed that these failures occurred by the screw rotating under cyclic loading conditions. This rotation of the screws appeared to be the only mode of loosening. No pullout or racheting out of the deck was observed. The testing of an antiback-out system shows no sign of screw backout, which implies that an anti-backout system can prevent screw backout on the roof.

NEW DEVELOPMENT

Many designs have been developed in an effort to eliminate failures caused by screw backout and pop-up. The designs of these products were the result of analytical studies of forces acting on the system. The three parameters important for prevention of back-out:

- Thread design (in case of wood and concrete shank design)
- Screw head design
- Plate design.

ANALYTICAL APPROACH

An inclined plane representing a screw thread is used. On this plane, we place a block that represents loading due to fastening into a metal deck (Fig. 1). If the screw thread is wiggled back and forth, the block will eventually work its way down the plane. This is analogous to the loosening or backing out of a screw. To retain a tight screw, the resultant screw tension should vary as little as possible. The slope of the thread angle and the helix angle of the thread can affect the tension of the screw. As the top slope of the thread angle gets smaller, the normal load will increase, thus increasing the tension load.

We resolve the forces and solve for a single-thread geometry (Fig. 4):

- The angle χ is the helix angle of the thread.
- Summation of all the unit axial force acting upon the normal thread area is represented by "F".
- Force "P" resist back-out and shear load.
- Friction forces that oppose back-out motion are the product of the coefficient of friction μ and normal force N, i.e. μ N.
- Circumference of one thread is π dm, i.e., $\pi = 3.1416$, dm = mean thread diameter circle whose height is lead "ℓ".
- F_H is the summation of all horizontal components of the forces.
- F_V is the summation of all vertical components of the forces.

The force systems are in equilibrium when

$$F_H = -P - N \operatorname{Sin} \chi + \mu N \operatorname{Cos} \chi = 0 \qquad (1)$$

$$F_V = F - \mu N \operatorname{Sin} \chi - N \operatorname{Cos} \chi = 0 \qquad (2)$$

Eliminating normal forces and solving it for P.

$$P = \frac{F(\mu \operatorname{Cos} \chi - \operatorname{Sin} \chi)}{\operatorname{Cos} \chi + \mu \operatorname{Sin} \chi} \qquad (3)$$

Dividing numerator and denominator of this equation by Cos χ and using relationship $\tan \chi = \frac{\ell}{\mathrm{dm}}$

$$P = \frac{F[\mu - (\ell/\pi\,\mathrm{dm})]}{1 + (\mu\,\ell/\pi\,\mathrm{dm})} \qquad (4)$$

Torque is the product of force P and mean radius dm/2.

$$T = \frac{F\mathrm{dm}}{2} \cdot \frac{\pi\,\mu\,\mathrm{dm} - \ell}{\pi\,\mathrm{dm} + \mu\,\ell} \qquad (5)$$

This is the torque required to overcome a part of friction as the screw backs out. Where the lead angle is large or the friction is low, the screw will back out without much effort. In such cases, the torque T from equation (5) will be negative. When positive torque is obtained from this equation, the screw will provide maximum resistance to backout. Maximum resistance to backout can be achieved when the coefficient of thread friction is equal to or greater than the tangent of the thread helix angle.

$$\mu \geq \tan \chi$$

CONCLUSION

As the back-and-forth movement of the screw head increases, so does the horizontal loading on the fastener's threads. This increased horizontal loading easily overcomes frictional forces, thus causing the screw to backout. Minimizing pivoting of the screw head with respect to the plate (Fig.5), proper thread design and consideration of insulation rigidity can yield optimum backout resistance. The single-ply and insulation head-locking plates are design solutions for this problem. Lab tests have shown that ordinary single-ply membrane plates start backing out as early as 89 cycles, while Gearlock-type plates (after 2,000 cycles) do not back out at all.

CORROSION

Another current industry concern is fastener corrosion. There have been long-life coatings available for some time, but until recently, there were no minimum standards to evaluate these coatings. After the initial phase of using phosphate and oil, zinc plated fasteners came into use for corrosion resistance. Zinc plating became the industry standard for corrosion resistance fasteners in the late '70s and early '80s. When fastener usage increased due to re-roofing application, rusting became an issue. As good a plating as zinc was, a better corrosion-resistant coating was needed to protect fasteners from excessive moisture present in old insulation. The industry developed a number of long-life coatings. It was assumed that all these coatings were indeed long-life coatings. However, no criteria existed to evaluate them. Minimum standards were needed to judge their performance. Fastener manufacturers under the Single Ply Roofing Institute umbrella and Factory Mutual developed a test procedure to measure the corrosion resistance of long-life coatings. They also developed minimum performance requirements for acceptability. The fastener should not accumulate more than 15 percent red rust after 15 cycles of modified DIN50018 2.0 liter Sulfer Dioxide test. (see FM 4470 Class 1 Roof Covers). The standard requires approximately three times more corrosion resistance than a zinc-plated fastener. In 1983, only a few fastener manufacturers could have met the standard. Today, 75 percent will meet this minimum standard. Some manufacturers provide superior corrosion protection coatings that go beyond the minimum standard.

In spite of the availability of long-life coatings, installation into wet insulation is not approved. There is no established criteria to measure the moisture content present in insulation and its damaging effect on the roof-fastening system. Precise judgment should be used. In all cases, fastening into wet insulation should be avoided. Stainless steel fasteners are not a solution where excessive moisture is present. Long-life coated and stainless-steel fasteners provide excellent corrosion resistance in normal atmospheric conditions and increase the life of a roof. Installing into wet insulation will be defeating the purpose of increased life expectancy of the roofing system. Corrosion is a natural process. If the conditions are right and moisture is present, corrosion will occur. It is everybody's concern in the roofing industry to minimize these conditions as much as possible; thus, whenever wet insulation is encountered, it is recommended that it be torn up and replaced.

FASTENER APPLICATION GUIDELINES

There are many application guidelines that should be followed routinely. Following are two guidelines which I consider most important:

1) For recovering, always take roofing core samples. It helps to determine the size and type of the fasteners that will be needed for the job. Core sampling will reveal the thickness of the insulation and condition of the roofing deck.
2) For re-roofing, always conduct a pullout test to determine the strength and condition of the deck. At least 10 pullout tests at different locations are recommended; more are needed if there is inconsistency in the pullout results. Most of the tests should be conducted in perimeter and corner areas, others in low-lying, leaky areas. Pullout tests of these areas are important because the corner and perimeter experience higher wind uplift loads. The presence of standing water makes a good target area for the test because of the deck's excessive exposure to moisture. Check the deck movement by pushing on it. Use of a portable pullout tester will make it easier to perform these tests.

REFERENCES

[1] George C. Beakley, H.W. Leach. Engineering "An Introduction to a Creative Profession."

[2] Factory Mutual Loss Prevention Data Sheet 1-28, 1983.

[3] "Corrosion is Major Danger for Fasteners," *RSI*, Jan. 1986.

[4] R.E.Petersen, "Stress concentration Factor," John Wiley & Sons, N.Y. 1964.

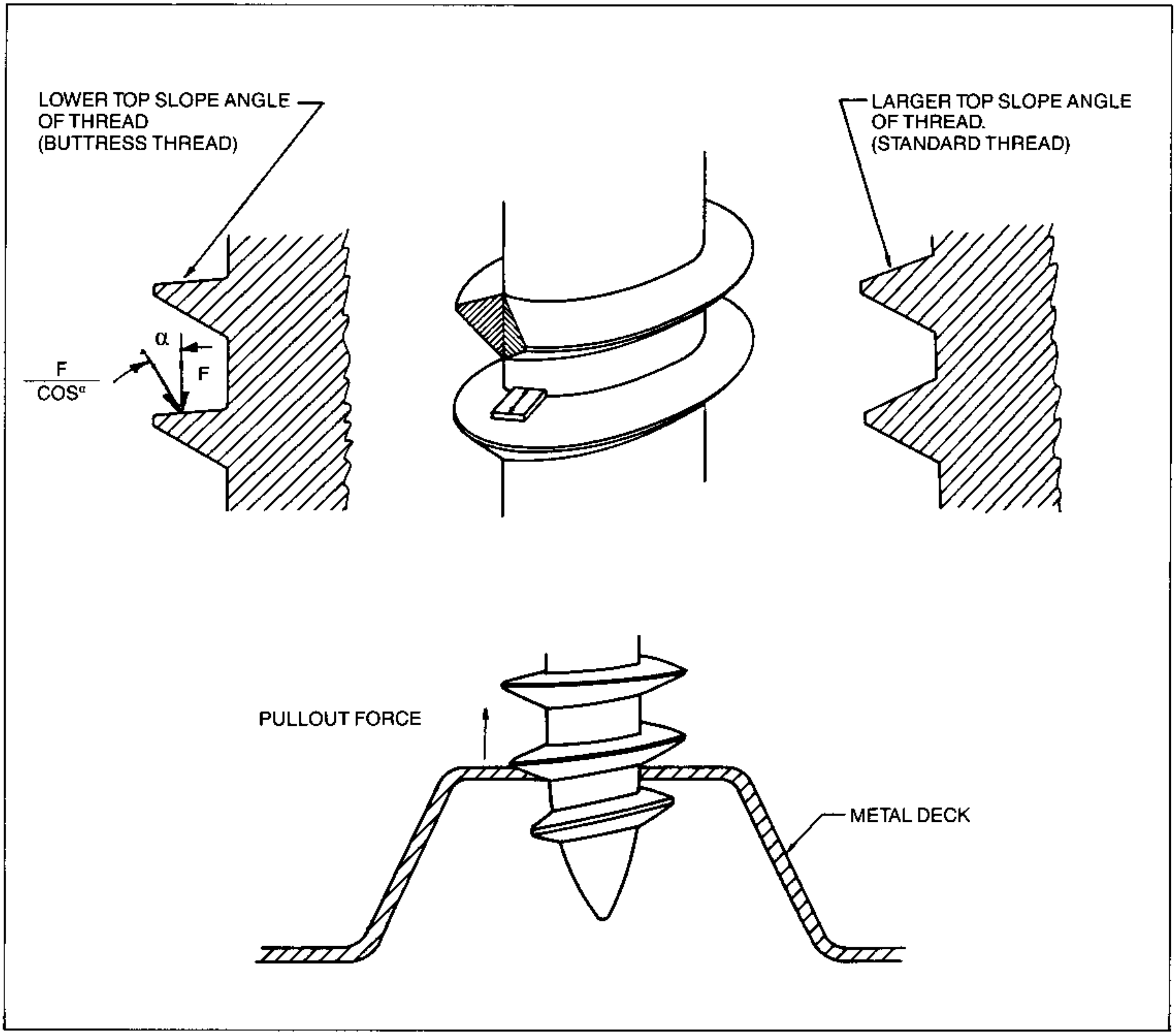

Figure 1 *Lower top slope angle of buttress thread increases pullout strength and resists fastener backout*

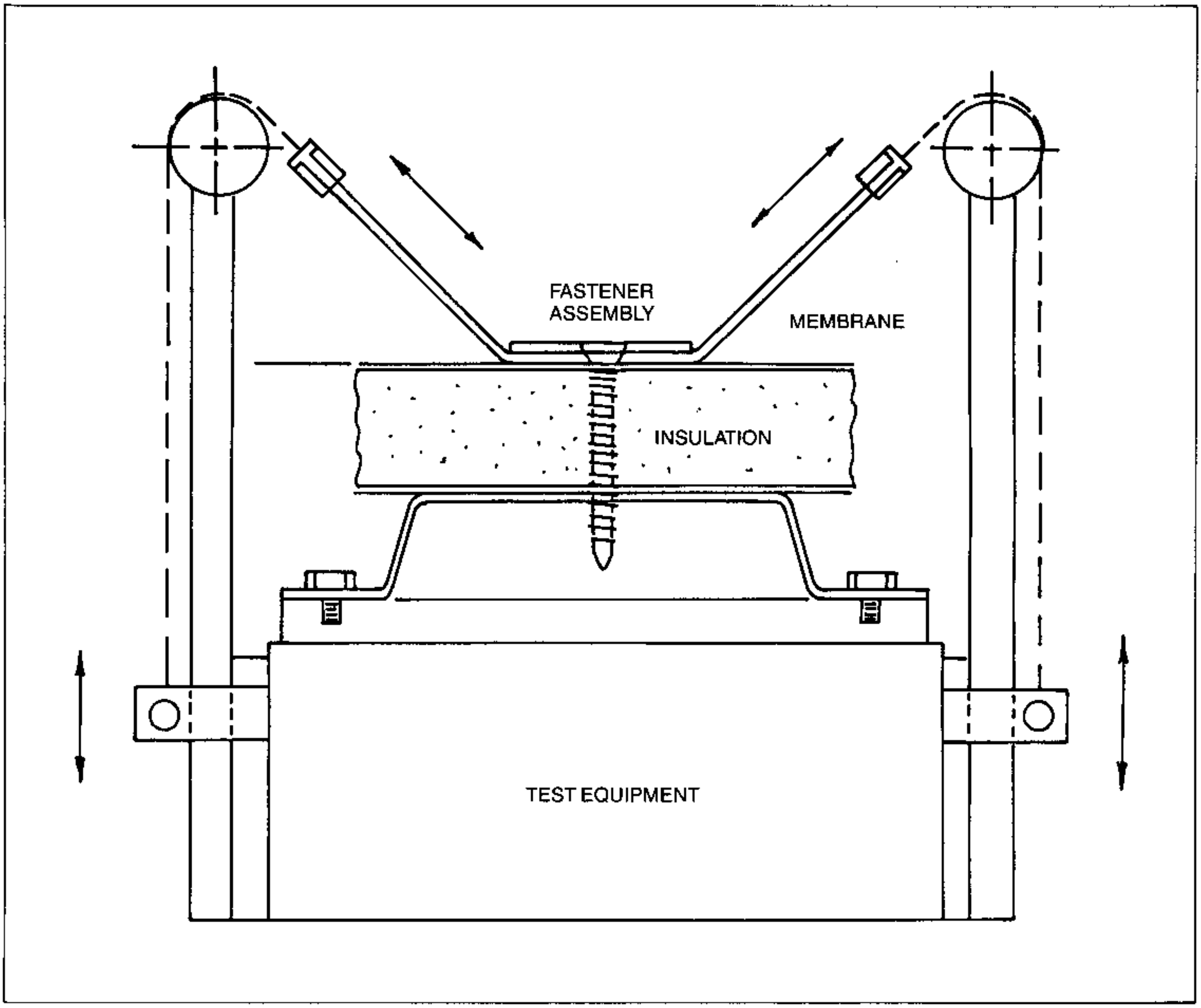

Figure 2 *Diagram of typical installation of test specimen on dynamic equipment*

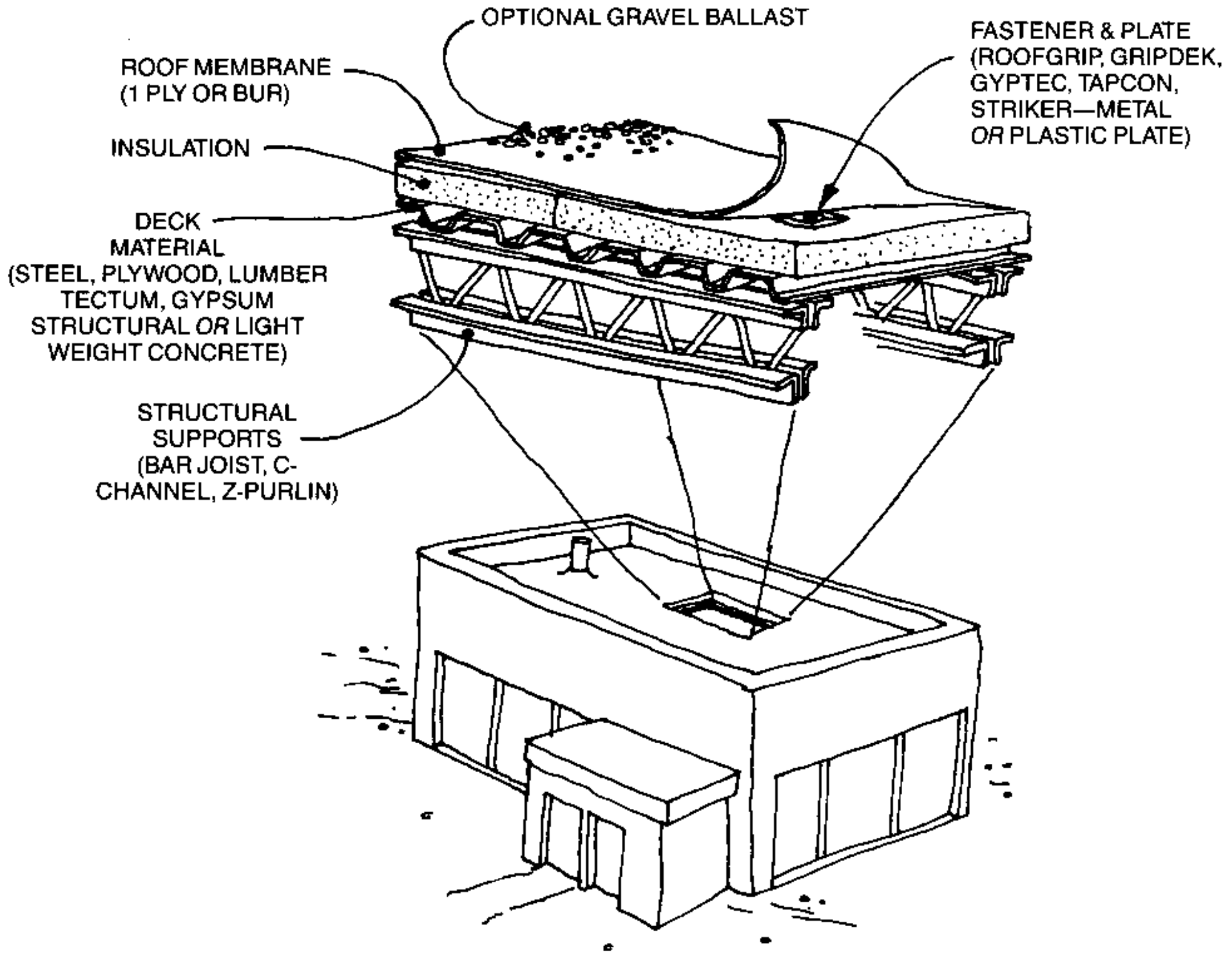

Figure 3 *Mechanically attached roofing system*

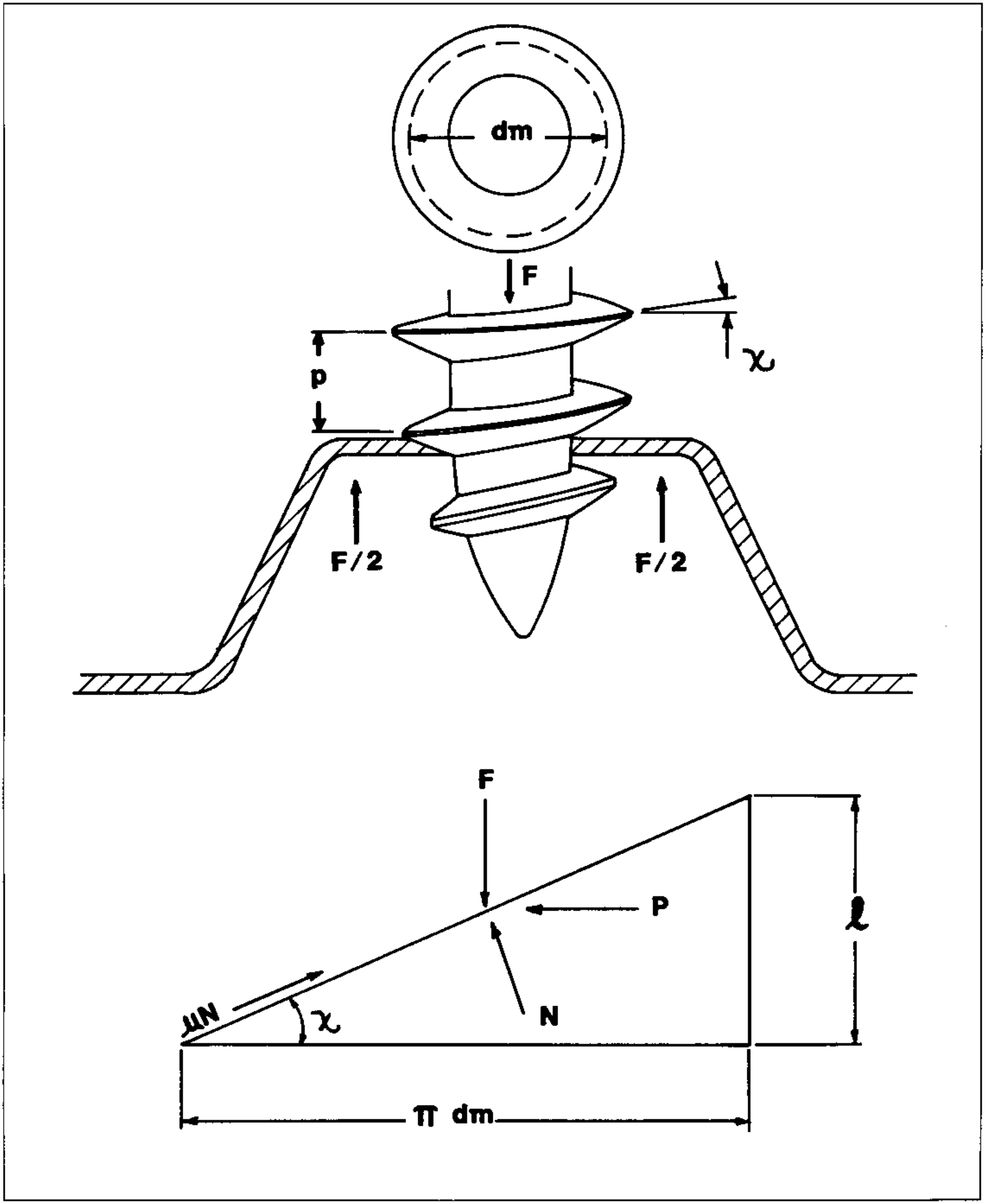

Figure 4

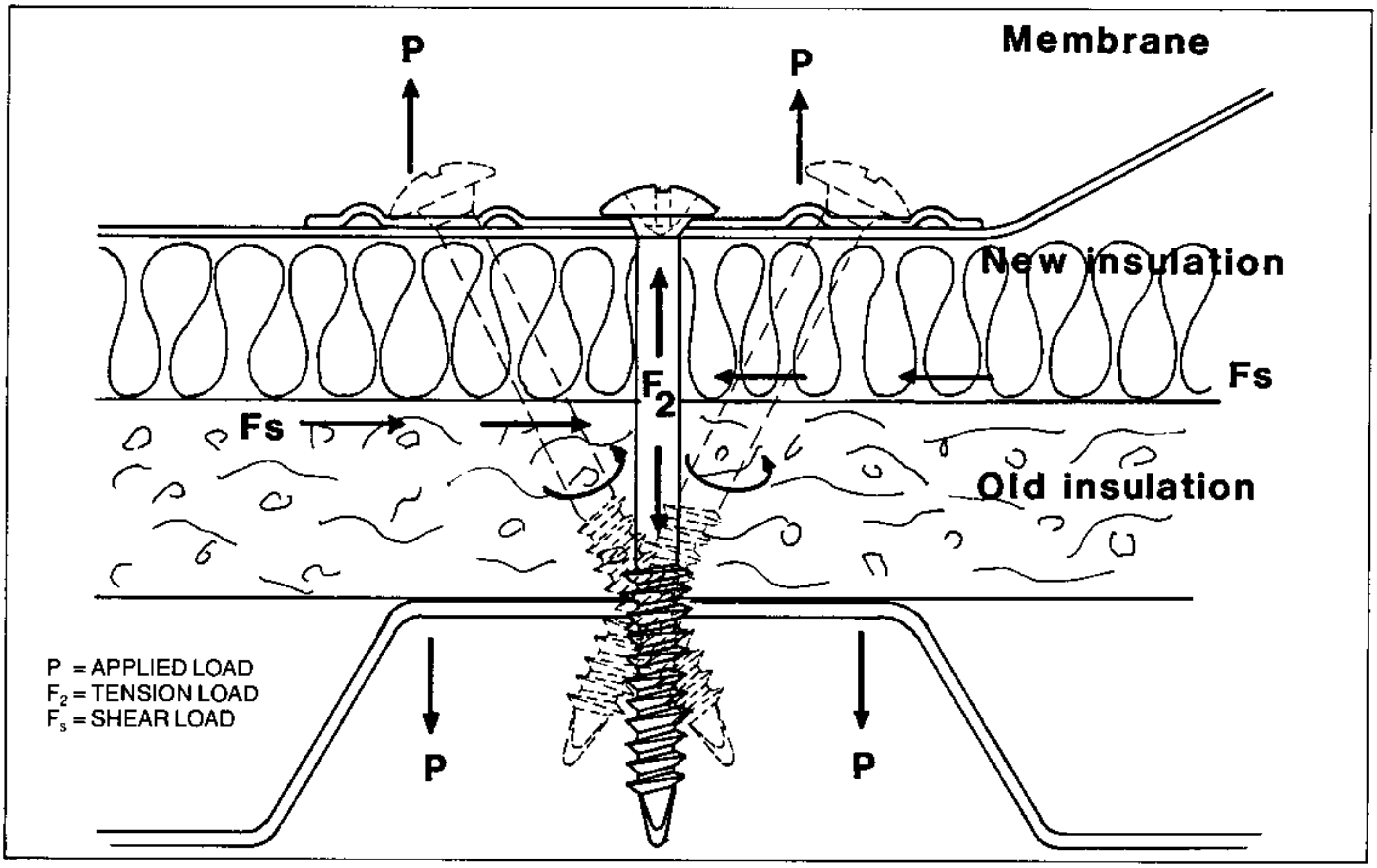

Figure 5

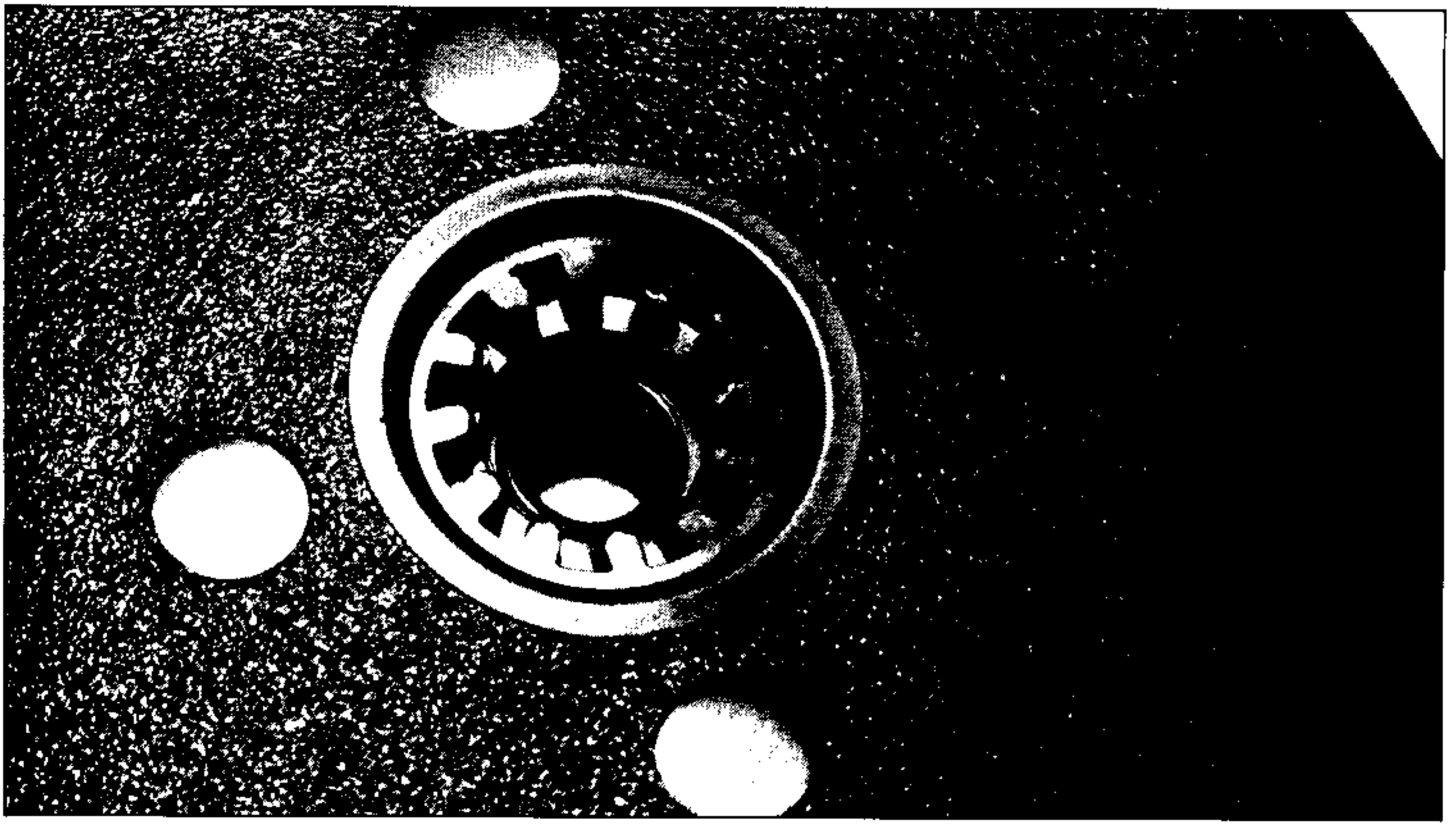

Photo 1 *Locking head gear plate*

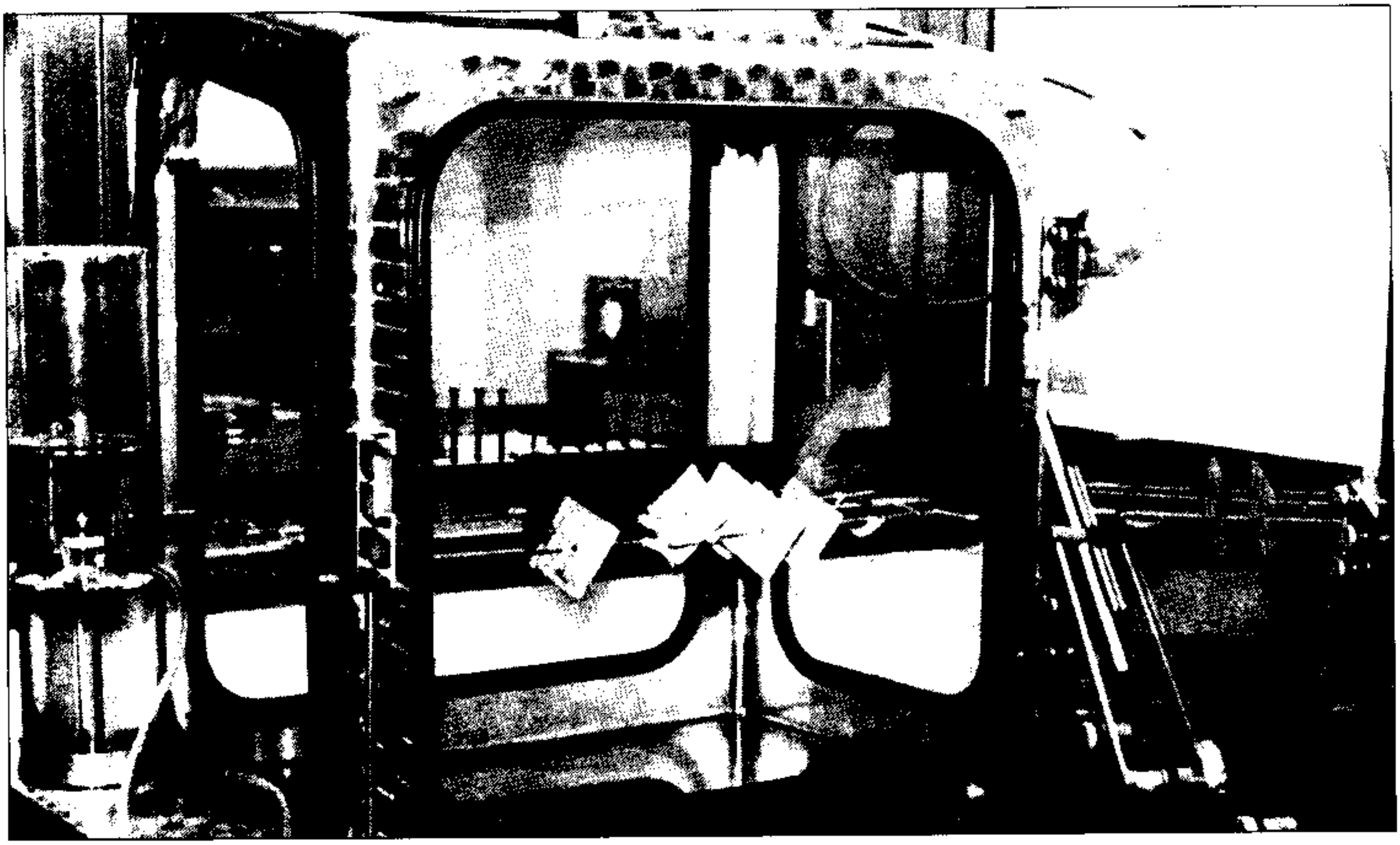

Photo 2 *Kesternich cabinet*

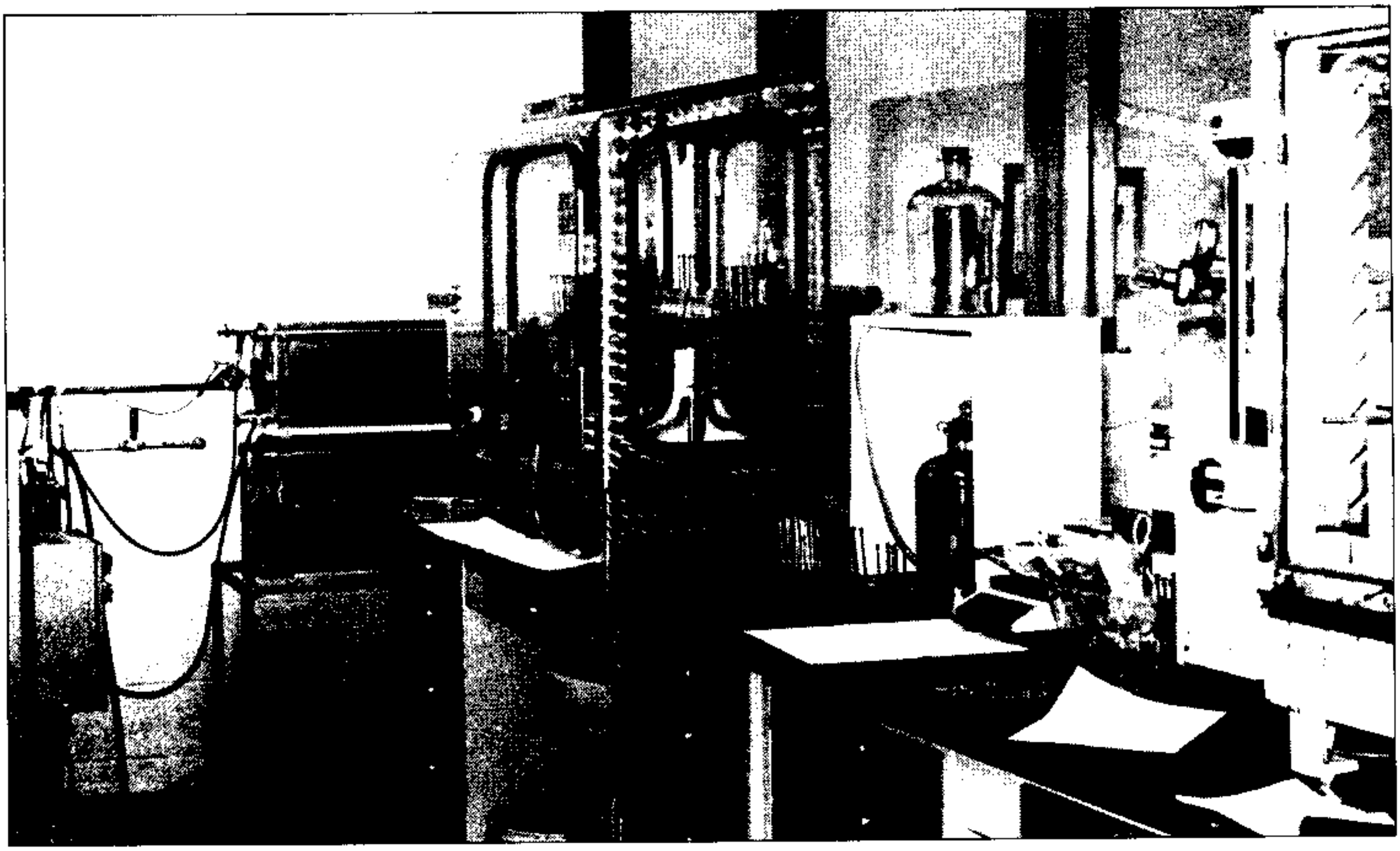

Photo 3 *Corrosion test laboratory*

Photo 4 *Insulation fastener sticking out due to old compressed insulation under the membrane*

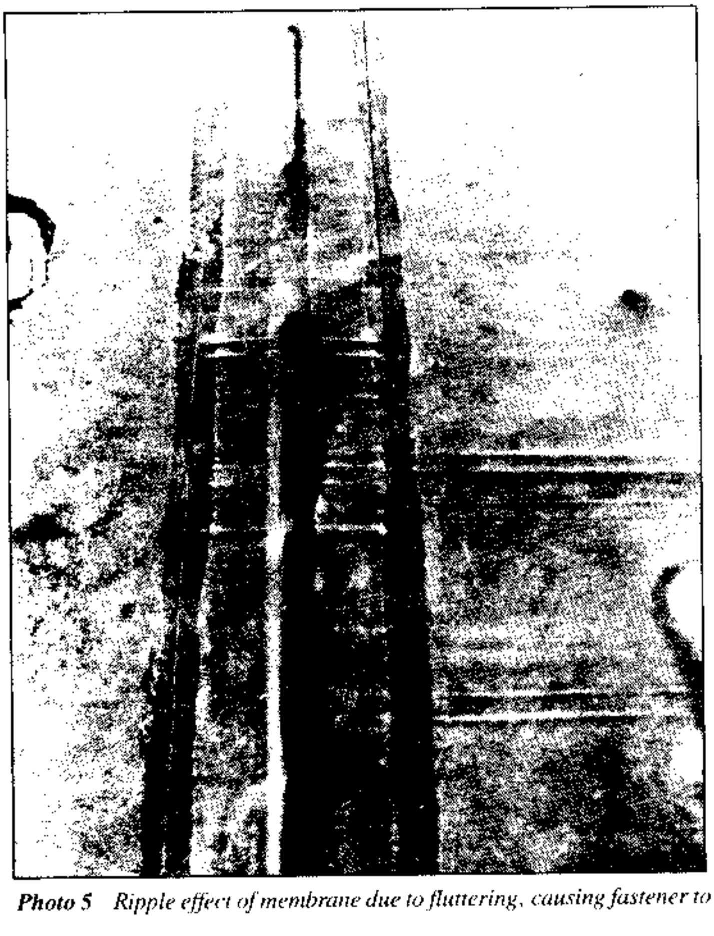

Photo 5 *Ripple effect of membrane due to fluttering, causing fastener to backout*