AIR PRESSURE TESTING OF SHEET METAL ROOFING

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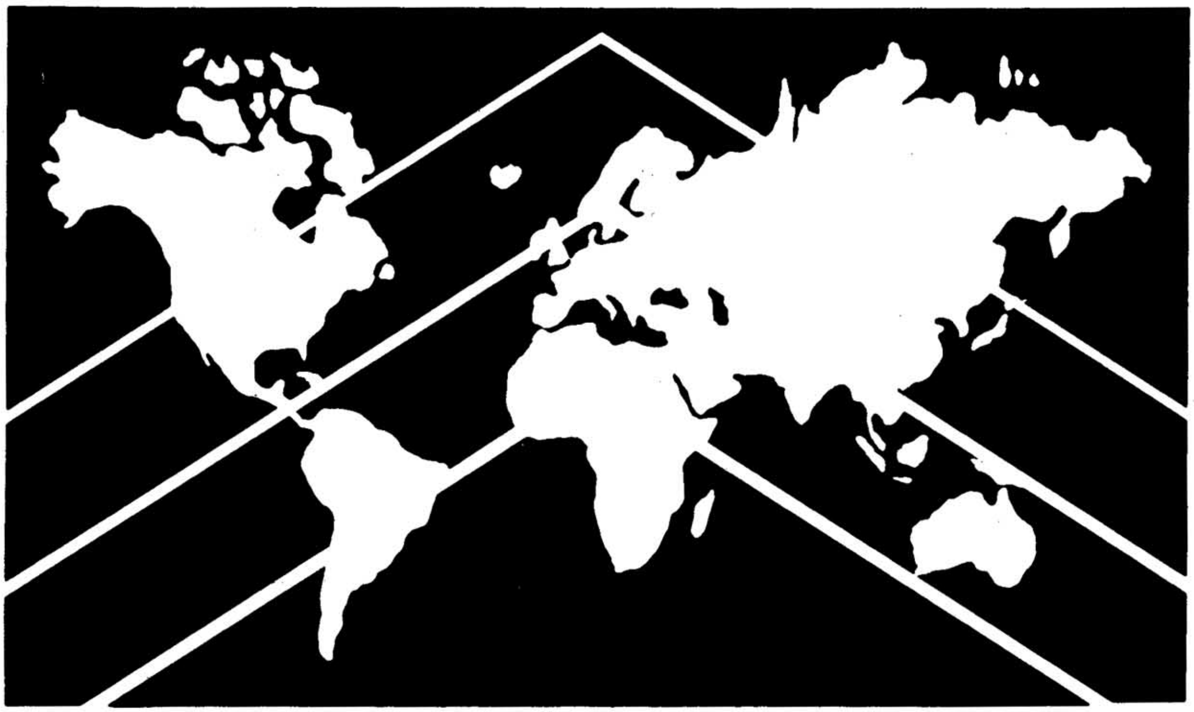
A Decade of Change and Future Trends in Roofing



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Computations and commonly used testing methods do not accurately predict the negative wind resistance of thin-gauge sheet metal roofing, particularly with the increasingly popular concealed fastener standing seam products. Crosswise distortion of profiles from air pressure can significantly change section properties to invalidate calculated capacities. Tensile tests that pull attachments from rigidly supported sections of roofing do not include the possible detrimental effect of distortion.

In the United States, air pressure test procedures developed for other products or materials are being used to qualify metal roofing without modifications to account for differences in behavior of the installed product. More elaborate test methods employed elsewhere in the world have similar drawbacks. The major problem is that perimeter attachment and seals of the typical air pressure test specimen structurally reinforce the test units. The test procedure outlined in this report has produced ultimate capacities as low as one-fifth of that produced by test setups constructed in the generally accepted manner.

CROSSWISE DEFLECTION—THE EFFECTS OF DISTORTION

Calculated Properties and Their Limitations

Computations are based on published equations developed from tests of specific profile elements. Most engineers prefer this design method for product design because it is a relatively simple matter to evaluate variations of dimensions to arrive at an optimum shape. The procedure considers structural elements as strips or as parallel beams, and the flexural capacity is determined as a function of section properties and spacing of elements. The only crosswise considerations made are to determine the effective width of flats or stability under compression loading.

Under uniform positive pressure, the wide flat between ribs of a standing seam panel bends downward. In this report, all crosswise bending such as this will be referred to as distortion to avoid confusion with deflection between supports. Positive pressure distortion for trapezoidal ribbed panels may be slight because the channel shape already approximates a catenary curve, and most load is carried in tension. With vertical ribs, the distortion is more pronounced.

The general result of positive pressure distortion on a ribbed panel is to increase the effective height of the rib and, therefore, increase both moment of inertia and section modulus. The shape becomes both stiffer and stronger. This increase in load-carrying capacity certainly is a valid benefit that could lead to more efficient use of materials, but the primary purpose of this report is to point out the significant *loss* of strength that occurs in the case of negative pressure or uplift.

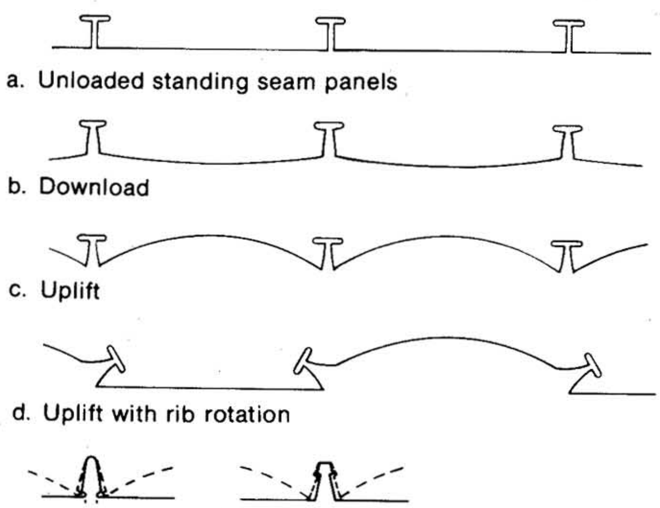

Figure 1 Distortion from uniform air pressure

Under uniform negative pressure, illustrated in Figure 1c, distortion reduces both moment of inertia and section modulus. In such cases, panels with sloping ribs appear more susceptible to change than panels with narrow vertical ribs. As pressure increases, further distortion of the middle flat induces a torsional force on the ribs which is balanced by the adjacent panel and resisted by clip rigidity. Depending on the perimeter attachment, the edge rib may be more or less resistant to rotation. Failure by rib rotation and subsequent buckling may be more significant for panels with symmetrical tall, narrow, vertical ribs than with trapezoidal ribs. To obtain test results comparable to the behavior of a full-size roof, the edge support and the number of panels in the test setup are important. With only four panels across, our tests showed that three intermediate ribs were more stable than a larger number. When the number of panels was increased to five or six, the test assembly was less stable, and adjacent ribs rotated in opposite directions at lower values. This was accompanied by alternate flats rising while the others moved downward (toward the pressure) (*Figure 1b*). This distortion could continue without increase in air pressure until a new level of stability was reached. With some attachments, the rotation was catastrophic. Others withstood this condition, and when pressure was removed, returned to very nearly the original position (*Figure 2*). With some clips, panel seams failed before the attachment, indicating a product limit independent of anchor spacing and solely a function of panel material properties or profile.

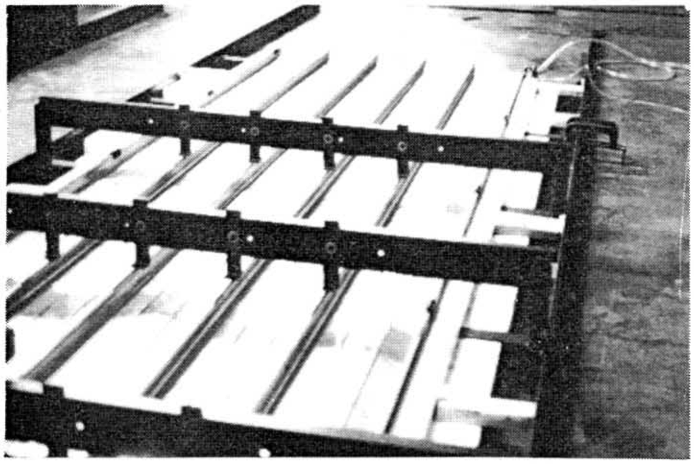

Figure 2 *Permanent set from rib rotation*

Attachment Clip Pullout

Even at small pressures, a standing seam rib is spread apart by arching of the flat. Products secured by internal attachments at some point on the vertical surface of the rib are particularly vulnerable to being "unlatched" unless the internal anchor has the resiliency to follow the sides of the rib as it spread. (*Figure 1e*). Obviously, a pull test from rigidly supported sections of this type of product does not represent the capacity when subjected to air pressure. Even with screw fasteners, combined stresses can cause pull-through of the fastener heads at values lower than for straight pullover tests of fasteners from flat sheet. This can occur for uplift loads with screw fasteners in highly stressed areas close to ribs or in the middle of narrow flats between pairs of ribs.

Recognizing that concealed clip systems have strength that can vary with the applied pressure, it is convenient to plot load capacity as a function of pressure. On this type of chart, the four possible modes of failure have curves as illustrated in Figure 3. The maximum load is the capacity based upon the strength of the clip independent of applied pressure. At some pressures, capacity may decline as distortion affects clip engagement. At either end of the pressure scale are the limits of the panel itself; flexural bending strength governs at the lower end while seam strength establishes the upper limit. Segments are drawn as four distinct, discontinuous curves because the mode of failure in each can be independent of the others. Clip failure can be by tearing or bending from eccentric load unrelated to the distortion in the panel itself. Rib or panel buckles from bending stresses may be influenced by the pressure changes of the profile but are distinctly different from attachment failures. Seam strength may be closely related to the clip-in-seam capacity since a seam failure may be precipitated by the prying action of the clip itself, while in other cases the seam can open with the clip remaining engaged.

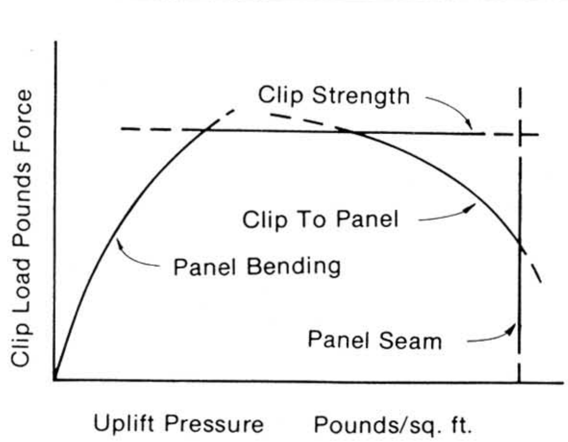

Figure 3 *Possible limits of uplift capacity*

Points for the curves are determined by testing at various span lengths continuous over several supports. Clip loads are computed on the basis of the appropriate reaction factor for the number of spans involved. For example, the load is 1.25 wl at the middle support of a two-span condition and 1.1 wl at the interior supports of a three-span set up. In addition to ultimate capacity, the plot of yield loads is also important.

Actual ultimate loads for one roof product with several different clip attachments are shown in Figure 4. Along the zero pressure ordinate are two values developed by conventional tests. Correlation of these two values with the air pressure tests is good only for clip A* and curve A which are relatively insensitive to pressure distortion. Curve B, which shows a rapid decline in capacity as pressure reaches 90 pounds per square foot, does not relate well to value B*.

Curve C demonstrates an anchor system that is insensitive to pressure. The clip strength is high enough to intersect the moment capacity of the panel at the lower pressure (longer span) and is flat virtually to the limit of seam strength. In this test, clips remained engaged to one panel edge while the seam pulled apart at a pressure of 159 pounds per square foot. (7.6 kPa).

Distortion values—Crosswise Deflection Measurements

Distortion of the flat pan is primarily a function of crossribs, pan width, material properties and sheet thickness. However, rib configuration and rigidity of the connection between individual panels has an effect which can be determined only by testing. The most significant factor in tests conducted to date is width. The "Specifications for Aluminum Structures" was revised in 1982 to recommend air pressure testing whenever the width thickness ratio exceeds certain factors involving design load and tensile yield of the material. Because distortion is nonlinear, criteria based upon distortion at the design pressure such as this can be misleading.

Typical values of crosswise distortion from specific product tests of standing seam panels in 12- and 16-inch widths are shown in Table 1. These are from tests of specific proprietary profiles and are not necessarily indicative of other products but show inconsistent variation with gauge and material properties.

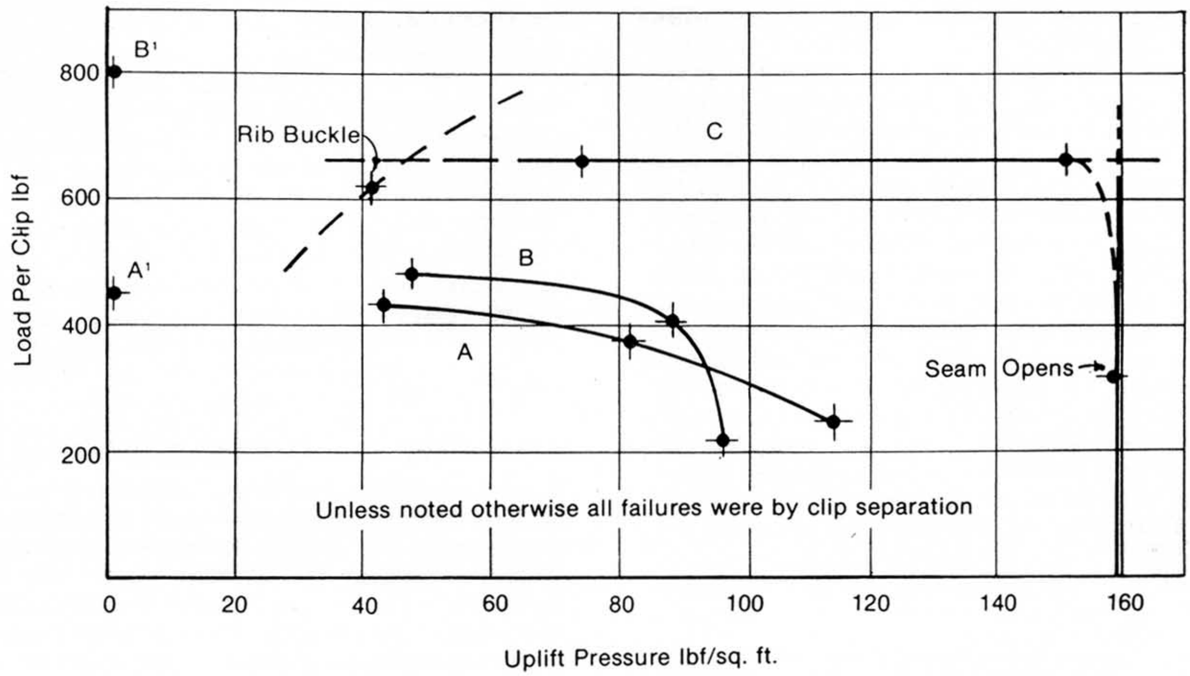

Figure 4 Ultimate loads for three different clips

(kPa) Pressure in psf Product	(.96) 20	(1.9) 40	(2.9) 60	(3.8) 80	(4.8) 100	(5.7) 120	(6.7) 140
12″×22 ga steel	1/8″	5/16″	1/2″	3/4″	1 1/8″	4″	4 3/8″
16″×22 ga steel	5/8″	1 3/4″	2 1/2″	3″			
12″×24 ga steel	1/4″	5/8″	1 1/2″	4″			
16″×24 ga steel	7/8″	2 3/8″	2 3/4″				
12″×.040″ aluminum	1/8″	5/16″	9/16″	3/4″	1 7/16″	1 1/2″	
12″×.032″ aluminum	1/2″	1 1/4″	2 3/4″				
16″×.032″ aluminum	2 1/4″	4 3/4″					

Table 1 Upward distortion of middle flats from negative pressure

The significance of specific distortion values will vary with the configuration and the method of anchorage. Flexural properties appear to be significantly reduced when the distortion approaches 50 percent of the rib height. Attachment capacity depends in large part upon the specific design; some are sensitive to minor changes in profile while others, like the product curve C in Figure 4, retain their capacity up to the strength of the seam itself.

PERIMETER CONDITIONS OF THE TEST FIXTURE—PREFERRED PRACTICE

End Condition

Industry practice calls for additional fasteners in the flats of most sheet metal panels at all eaves and ridges. When used on a test fixture, this also simplifies the end seal. However, these extra attachments restrict the upward distortion of the panel between the anchor points and produce a condition that does not occur in the middle of a roof. Figure 5 shows a typical eave condition under uplift pressure. This effect was reported by J. Rovere in a 1965 article describing results of air pressure uplift testing of roof panels conducted at the Centre Technique de l'Aluminium.

With anchor clips that are sensitive to distortion, pullout resistance within 4 feet of the eave can be double the strength of the connection located at a distance of more than 8 or 10 feet away. In tests of 12-inch and 16-inch wide panels, the end effect was found to influence results as much as 12 feet away when both ends of the test fixture were secured with fasteners.

Air pressure test procedures developed for built-up roofing such as the UL 580 test do not address this potentially significant factor. In this test, roof anchors are permitted within 2½ feet of the closely spaced attachments at the end

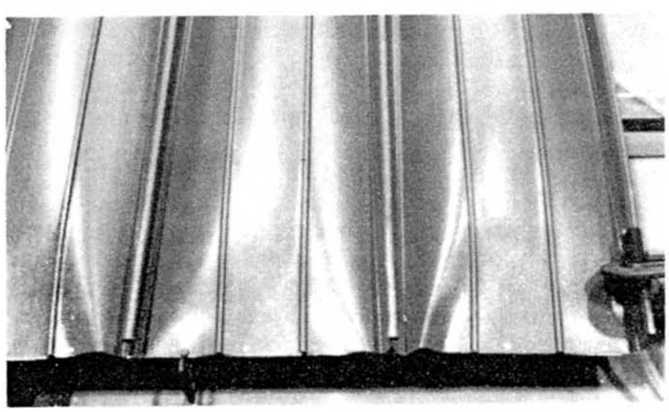

Figure 5 Distortion at eave condition

seal. One product can safely carry repeated pressure applications up to 105 pounds per square foot in this test yet fail at less than 60 pounds per square foot of static pressure when the end seal is removed.

Since test chambers significantly longer than 25 feet are economically burdensome, it is preferable to develop end conditions that do not influence crosswise distortion. With current codes requiring higher uplift resistance at the eave conditions, determining anchor capacity at specific distances from an eave as well as at the middle of the roof may be valuable. In such cases, employ a standard eave detail at one end of the test specimen and leave the other free of crosswise restraint. Air seals at the free end of the panel must be flexible enough to follow the panel distortion. When air pressure is used directly against the underside of the test specimen, such a seal can be fabricated by taping short sections of polyethylene film to the underside of individual panels. The ends and edges of these sections may be sealed together, and the excess confined by an end restraint that prevents billowing beyond panel ends. Pressure should be applied to the full length of the test panel to prevent any unloaded section from acting as a partial restraint to crosswise distortion. This end seal construction is illustrated in Figure 6.

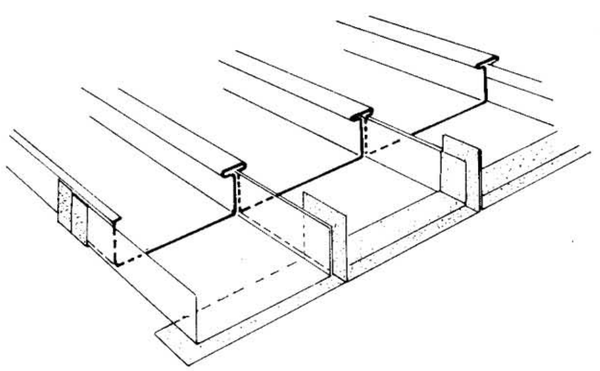

Figure 6 Flexible seal for end conditions

If seam sealant is not a standard item for the product, it may be necessary to use grease or non-curing sealant as a seam seal to avoid affecting results.

Edge Conditions

Development of an edge condition that neither restricts distortion nor unduly increases the tendency for imbalanced deflection of adjacent spans may require some judgment. With panel seams at the rib, the two edges usually are not symmetrical, and the "half-rib" may be totally inadequate to carry half the load. Conventional practice is to split a panel in mid-flat and to use fasteners on close spacings to clamp to the edge of the test fixture (Figure 7). At longer spans, this can restrain mid-span deflection and induce twist in the rib. If stability of ribs is adversely affected, the edge support may be designed with lengthwise ridigity in proportion to its share of the full panel load.

When tests are conducted with artificial edge conditions, the standard detail should be investigated to ensure that it can match the performance of the main roof. In all cases at least five full pan widths across the test fixture is recommended to assure full development of panel distortions.

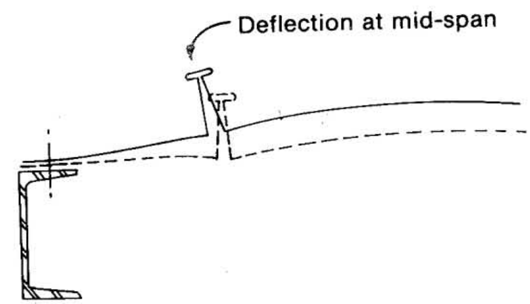

Figure 7 Conventional edge seal

APPLICATION OF AIR PRESSURE—AIR BAG DESIGN

The basic principles of conventional air pressure testing of building components are described in ASTM E330 "Tests for Structural Performance of Exterior Windows, Curtain Walls and Doors by Uniform Static Air Pressure Difference." This standard expresses concern for use of joint or perimeter seals that could influence results and requires that the testing engineer comment upon these conditions. It does not make the testing engineer fully aware of the significant difference in results that occur with light polyethylene film bridging the gap between standing seam panels.

When air pressure is used, flexible seals are required at the ends and edges to keep air leakage within practical limits. Side seals may be complicated by the anchorage but can be a relatively simple fold of material confined between parallel faces at the edge of the test fixture.

Panel ends may be sealed by taping segments of flexible film to individual panels as illustrated in Figure 6. However, these can be tedious to install, and for a test program where a number of tests will be run with the same profile, a pleated airbag having a configuration similar to the end seal can give the same result. Pleats in the air bag are drawn up into the seams as individual panels are assembled. Properly placed pleats avoid crosswise restraint to spreading of panels and assure full pressure across the panel surface.

Some concealed clip designs may interfere with a pleated air bag. In such cases, either multiple pleats or a supplemental tubular air bag connected to the main air bag may give equivalent results. Results from a pleated air bag design should be verified by comparison testing with air pressure.

Air pressure testing without good seals at seams and edges requires a fairly large test setup, and because initial failure usually destroys the setup, less information can be developed from each installation. An air blower is required, and the pressure chamber must be large enough to avoid pressure variations from air flow in the chamber. However, with appropriate seals, ordinary compressed air can be used for supply; and more importantly, without a high air flow, the air chamber can be very shallow. In tests with about ½-inch clearance of the panels from the back of the pressure chamber, there is a significant drop in air pressure whenever a failure occurs. This drop can prevent progressive failure of adjacent attachments and permit the test engineer to immobilize the affected location with external supports for further loading to develop additional data.

Fatigue testing of Roof Attachments

Fatigue testing is not a desirable requirement for certification because of the relative expense associated with the longer term tests and the limited flexibility of the results. Cyclic load tests have been developed to account for the unanticipated poor performance of products in actual service. The results to date indicate that actual metal fatigue is not a factor with properly engineered products. With measurement of deflection and permanent set on panels at anchor points, it should be possible to detect the start of failure that goes unnoticed in the ordinary load test.

With the current building code sophistication of design for wind loads, there can be an infinite number of pressure values to apply to various parts of structures. Fatigue tests alone cannot produce the increments for efficient use of products because they are more in the nature of proof tests.

With appropriate simulation of service conditions and adequate factors of safety on yield and ultimate strength, products designed on the basis of static air pressure tests have performed well in fatigue tests and have given may years of excellent service in extreme weather environments. With further comparison of results from cyclic and static air-pressure testing, it may be possible to eliminate any need for the use of fatigue certification tests.

Test Fixture

Gravity forces have negligible bearing on results, so a test fixture may be mounted with panels on the floor or on a wall. A wall-mounted installation provides better access for observations or deflection readings and requires less floor space. However, panel installation may be difficult, and an air bag tends to sag out of position.

Construction of a test fixture is simple. Little specialized equipment is required, and the installation should be within the budget of may manufacturers as well as testing agencies. Ordinary available shop compressed air and industrial shop vacuum cleaners can provide adequate pressure for positve and negative pressure tests. To obtain higher vacuum at greater leakage, the power unit of a built-in residential vacuum system can develop over 300 pounds per square foot (14 kPa).

The basic fixture may consist of floor-mounted parallel angles with predrilled holes for anchorage of crosswise purlins at a variety of spans. Foam blocks between purlins to make a flush support for the underside of the air bag will conserve air volume.

After panels are in place, additional crosswise members may be installed to support the brackets which restrict failures and which may be lowered to support failed joints for further testing. Dial gauges are mounted on cross members independent of panel supports.

Instrumentation consists of dial gauges, a pair of slack tube water monometers connected to diagonal corners of the air chamber and an ordinary scale for other measurements. Individual air bags can easily be fabricated from four mil polyethylene film with duct tape. This entire assembly, which may occupy a space 12 feet wide by 30 feet long, can be removed for storage and reused at a later date.

If the floor slab is sealed or relatively free of cracks, positive pressure tests may be run on the same basic setup with vacuum pressure. In such a test, the pleated plastic film is fitted over the installation and sealed to the floor.

Test Procedure

Product certification should be made with production rather than prototype material. Where anchor strength is a function of fit between parts, the assembly should represent the minimum tolerance engagement.

Zero readings are taken at a nominal pressure somewhat in excess of the dead weight of the panels to take the looseness out of the assembly. One inch of water head (5.2 pounds per square foot) is commonly used. Loads are applied in convenient increments, such as 10 percent of the anticipated ultimate capacity, returning to "zero" between loads to record a permanent set of critical locations. In approaching the anticipated failure value, the increments may be reduced for greater precision.

Restraining brackets may be located ¼-inch to ½-inch above the ribs to prevent damage to dial gauges and to minimize the chance of overloading the adjacent anchorages when a failure occurs. As any anchor point fails, it is adjusted to provide support at the position just prior to failure. In this way, the braced connection will not carry more than its normal share of load when the assembly is repressurized.

Deflection readings taken at mid-span of panels are useful for determining effective moment of inertia at various pressures. In cases where the elastic deformation of the anchor-system is fairly large, this value may need to be developed to correct the reactions for differential displacement.

Records should include displacements and any surface buckles or "oil cans" that appear. Specifically, they should show the pressure at which these buckles are no longer elastic.

FACTORS OF SAFETY—REDUCTION OF TEST DATA

With several specific exceptions, the following approach is in accord with the procedures covered by metal industry specifications in the United States. In review of the factors of safety, the reader should know that some proprietary U.S. building codes include an additional factor of safety in the form of increased design load requirement for roof and sidewall connections. For example, the 1982 Uniform Building Code requires that cladding attachments be designed for an additional 17 percent to 45 percent of the pressure on the panels themselves.

Clip loads for specific tests are determined on the basis of the location of failure and number of spans tested. Reactions are adjusted as required for differential displacement of the loaded connections.

Design values are determined by applying an appropriate factor of safety to the mode of failure. Yield for panels or clips themselves is determined as the proportional limit of the deflection curve (which may be more noticeable on the permanent set measurements) or as the appearance of permanent surface buckles or creases in the non-structural flats of the panels. Ultimate strength is a rib buckle or separation of clip or panel seam.

	Other live loads	Wind only
Connection ultimate	2.2-2.5	1.65-1.88
Panel ultimate	2.0	1.50
Yield	1.65	1.24

Table 2 Factors of safety

Industry standards call for design values based upon the average of two or more tests. Because the allowable wind load increase can substantially reduce these margins, it appears more prudent to use minimum values. Also, since the proposed size of the test installation assures a minimum of four identically loaded attachment conditions, it should be reasonable to accept the results of a single test installation.

Panel weights essentially are negligible. The heaviest commonly used steel panel weighs about two pounds per square foot and aluminum half that. For uplift tests with the panel on the floor, it is conservative to omit the fractional portion of dead load called for in industry design; for live load tests the fractional portion of dead load generally is smaller than the precision of the test readings, but to comply fully with specifications, 50 percent of the dead load should be subtracted from the indicated applied load.

Ultimate loads should be corrected to allow for the properties of the test panels as compared to the minimum gauge and tensile strength of the specified production material. No increase is allowed for test panels below minimum properties.

Dividing both the corrected ultimate loads and pressures by the factor of safety produces allowable loads at given pressures. An exponential curve may be used to interpolate between points on the allowable design curve, but there should be no extrapolation of data outside test limits.

SUMMARY

With careful attention to perimeter conditions and to sealing between joints, static air pressure tests are a more reliable measure of the resistance of sheet metal roofing to negative air pressure than computations and mechanical pull tests. Three or four simple tests at different spans can be used to establish product performance through a range of pressure values.