National Severe Storms Laboratory
In-house memorandum in response to inquiries by the public following tornadic thunderstorms

THE WIND AND HOME CONSTRUCTION

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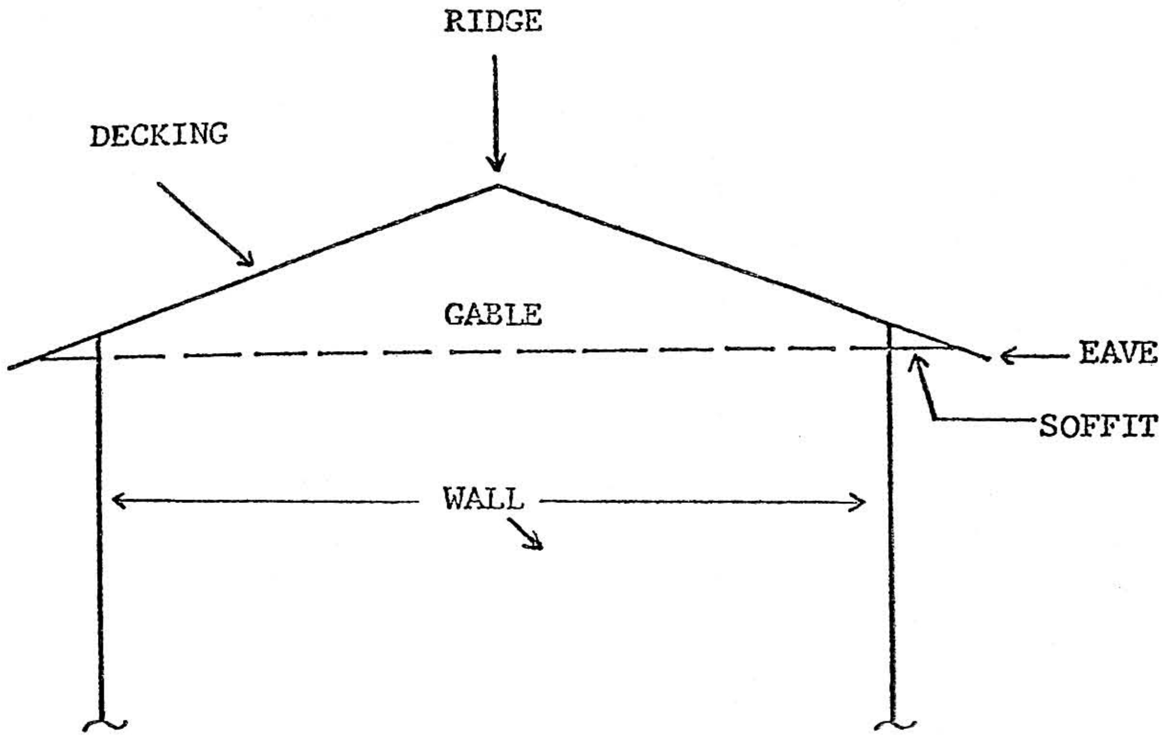
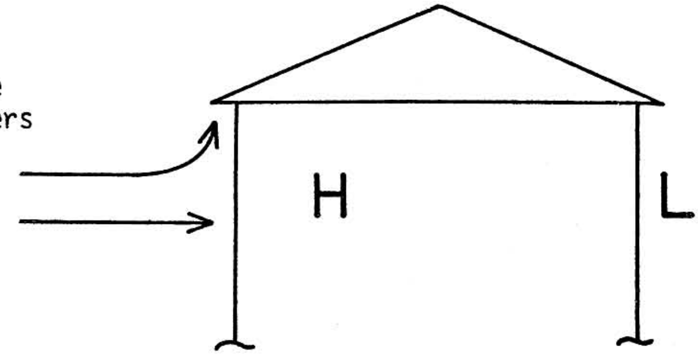
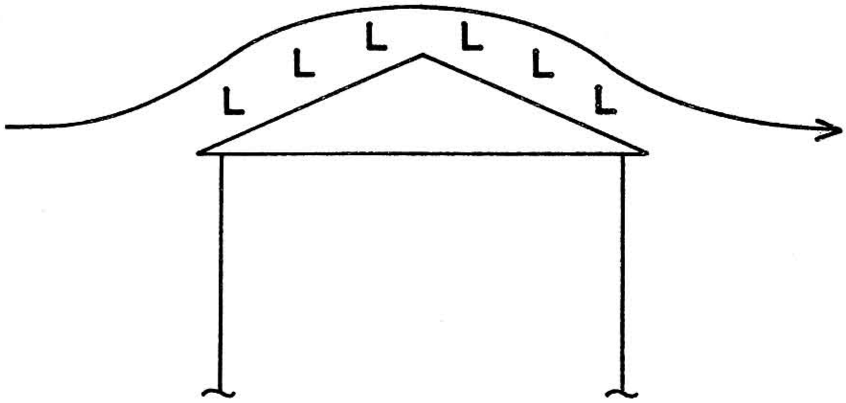


Figure 1. Terminology used for describing home components in this article.

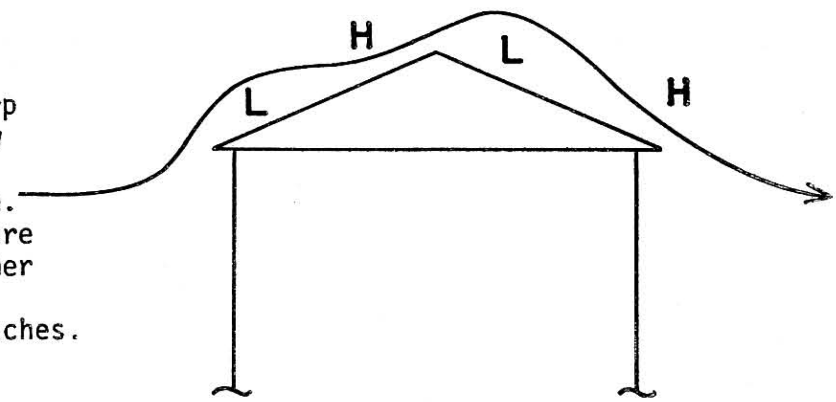
a. STAGNATION PRESSURE. Some of the moving air encounters the home and stops. High pressure builds up on the windward wall and soffit. (Low pressure is found on the leeward wall.)



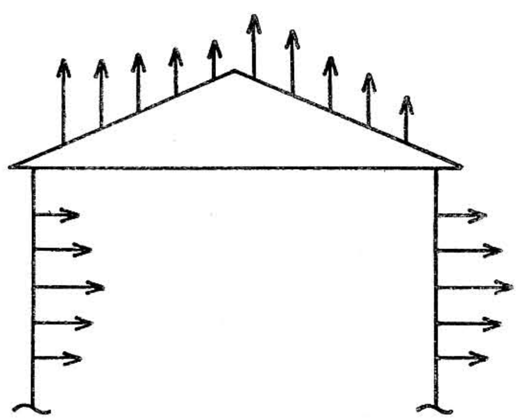
b. AERODYNAMIC PRESSURE. Air speeds up as it is forced to travel a longer path over the top of the roof, inducing a lowered pressure above the home.



c. SEPARATION PRESSURE. Sharp corners cause the air-flow to be "pushed away from" the structure, or separate. The result is lower pressure at separation points--higher pressure where the flow oscillates back and reattaches.



d. COMBINED EFFECTS. The combination of all of the above effects causes a lowered pressure above the roof that is an upward acting force.



1. INTRODUCTION

Each year high winds associated with hurricanes, tornadoes, thunderstorms and other severe weather events sweep away over a half-billion dollars worth of American property[1] and losses of this type are on the upswing as population and building increase.

In this article we show some simple and inexpensive methods which increase structural resistance to wind damage. The mechanisms of wind loading are described and a few ideas are outlined for reducing wind risk. For the sake of example, we deal with wind effects on a rectangular-shaped frame house with a gable roof, pitched 30 degrees to the horizontal, two foot overhangs at the front and rear eaves, and soffits under the eaves. Most of the principles can be generalized.

2. WIND EFFECTS ON A BUILDING

Without wind, the only force exerted by the atmosphere on an object is air pressure which arises from the weight of the overlying atmosphere. Atmospheric pressure acts evenly in all directions and on all parts of a structure (both inside and out) and the resulting force on the structure is zero. However, a number of imbalances in pressure occur when moving air encounters a structure and is forced to flow around it. First, near the lower center of the windward wall the air tends to stop completely at a spot called the "stagnation point" (Fig. 2a). The resulting increase in pressure on the wall can be approximated in pounds per square foot (psf) by the formula $P = 0.00205v^2$, where "v" is the wind speed in miles per hour*. Thus, a 20 mph wind causes a pressure of $P = (0.00205) \times (20) \times (20) = 0.8$ psf, while an 80 mph wind results in a pressure of 13 psf. A few windward wall pressures for various windspeeds are presented in Table I. Also, the portion of the flow which hits the wall and is deflected upward causes a similar upward pressure on the soffit.

Another type of imbalance occurs because air, deflected around an obstacle, must travel a longer path to reach the same point on the

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*$P = (0.8)(.00256)V^2$; 0.8 = pressure coefficient as given by ANSI A 58.1-1972.

downwind side than it would if the obstacle were not there. The principle is the same as for an aircraft wing. The top of the wing has a greater surface area than the bottom and the air must accelerate as it goes around the obstacle. The pressure is accordingly redistributed, with decreased pressure where the air moves fastest. This "aerodynamic effect," in the case of a building, causes outward acting pressure forces on the two side walls, the leeward wall and the roof (Fig. 2b). This effect can cause a pressure of roughly 50-100% that of the windward wall pressure, P. In this paper we utilize a value of 75%.

A third wind effect occurs because air cannot precisely negotiate the sharp corners of a building. The flow is deflected outward even further by this effect and "separates" from the structure, thus creating a drop in pressure to the lee of corners, ridges and eaves (Fig. 2c). Although the precise value of this reduction is difficult to calculate exactly, most wind engineers agree that the force is at least equal to that which exists on the windward wall, and probably larger*. In fact, studies have shown[3] that the effect may be more than twice as great as the figures shown in Table I. Thus, the magnitude of the combined upward force in a 75 mph wind, blowing perpendicular to the obstacle, would be at least 32 psf and could be as great as 43 psf. (It might also be mentioned that, on the average, the corners of the roof are most susceptible to damage, since some portion of the windward corner is always perpendicular to the flow, whatever the angle of attack. Therefore, the corner bears direct force most often.)

Finally, because the wind near the earth's surface is usually turbulent and gusty, none of the above effects are steady. In the case of separation, for example, this unsteadiness gives rise to turbulence in the wake of separations which affect wall components, roof components, etc. This turbulence can add appreciable extra force for short periods at various points around the structure. With all of these factors in mind, we now look at a sequential description of how our example structure might fail in a high-wind situation.

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*Values calculated for the home in this example vary somewhat for other types and shapes, but the conclusions reached are generally the same.

3. STRUCTURAL FAILURE OF A HOUSE

As the wind envelops a building, increased pressure occurs almost immediately on the windward wall and on the soffit above the wall. However, the first actual damage generally occurs at regions of the roof downwind of separation points. The wind which had been "pushed away" from the eaves oscillates back toward the house and "reattaches" to the roof. At these points, loose shingles (even slightly loose) come under stress, since any wind which wedges beneath a loose shingle exerts an upward pressure force and begins tearing it from the roof. For example, shingles commonly weigh 2 to 3 psf. An equivalent upward pressure can be generated by a wind of only 35 mph (Table I). That is to say, without any fasteners to hold them down, shingles would begin to lift at about 35 mph. Even if fasteners are in use, but have loosened, windspeeds of 75 to 90 mph are generally sufficient to tear shingles away from the roof. Furthermore, as the wind speed varies, the location of the reattachment zone varies--effectively "searching out" weak spots.

Wind tunnel experiments[4] and studies of actual wind damaged sites[5] have shown that, in most cases, the first true structural failure (i.e., after shingle damage) occurs at the roof. For a house without soffits, the total upward wind force is concentrated on the underside of the overhanging roof decking. Suppose the roof is composed of 1" x 8", reasonably seasoned, utility grade cedar or pine planks* which are fastened with two 8d nails (or equivalent fasteners) at each truss (2 ft. center to center spacing). Suppose this deck is then covered with felt and asphalt shingling. The total weight of the materials is about 5 psf. It is evident that the nails must supply the bulk of the resistance to the upward pressure force (5 psf can be offset by a 50 mph wind -- Table I). According to engineering tests[6], the resistance to withdrawal in the case of 8d nails used in the wood as described above is about 30 psf per nail (assuming a 2" nail penetration), or 60 psf**. Thus, the total resistance (weight of the materials plus withdrawal strength of the nails) is about 65 psf--approximately the same upward force generated by a 100 mph wind (Table II).

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* Computations yield similar results for 4' X 8' sheets of 1/2" plywood.

**G= 0.34; P decreased by 33 1/3% for gust impact[7].

When do winds reach these speeds? Winds of 100 mph or more have been recorded or calculated near large thunderstorms, in mountain induced wind outbreaks (occasionally), in hurricanes (often) and in tornadoes (regularly). It is clear that the amount of wind required to begin tearing off the roof of a house without soffits is well within the realm of what occurs in nature.

But our example home has soffits and the wind force is consequently split--the windward wall pressure pushes directly on the soffit, while the separation and aerodynamic pressures create lift on the decking. In the absence of complicating factors (such as open windows) the separation pressure is still sufficient to begin creating damage on the roof at speeds of 135 mph or more (value estimated from Table I plus 75% for aerodynamic lift). That is to say the upward separation - aerodynamic pressure force generated at 135 mph (65.5 psf) exceeds the resistance of the deck (65 psf). At this speed shingles and planks may begin to lift at points just downwind of the forward eave and center ridge. When this occurs the pressure inside the house can drop, as the low separation pressure vents the house, adding inward force to the walls--including the windward wall which already has inward acting stagnation pressure. The extra force may be enough to buckle this wall, particularly if roof-to-wall connections are weak. This is one of the more classic failure sequences. However, it may be seen that by adding just one or two more fasteners to each of 5 or 6 planks beside the ridges and eaves (at each truss), the resistable wind increases to as much as 170 mph. For a home with 2000 sq. ft. of living space, this may be 10 extra pounds of 8d nails (or equivalent fastener). Even better, the addition of an extra nail or two at each contact point over the entire roof would be no more than 25-30 pounds. This reinforced decking would be likely to resist separation by all winds except the very strongest of hurricanes and all but the strongest tornadoes (less than 2% of all tornadoes contain winds in excess of 170 mph).

The roof, however, is still the weak spot if it isn't fastened to the walls properly. This is because the total material in the roof, including trusses, is actually quite light on a unit area basis. Thus, even though a 2,000 sq. ft. roof may weigh as much as 20,000-24,000 pounds, notice that the mean distributed weight is only 10-12 psf. So again, most of the resistance to lift in strong winds lies in the fasteners. In some areas of the country, builders attach the roof by toe-nailing trusses to the exterior walls with two or three 16d nails at each truss-wall intersection. In many cases this technique will suffice. On the other hand, many cases exist in which toe-nailing is hardly adequate. Test results indicate that the resistance to withdrawal in the case of 16d nails is about 130 pounds (assuming a 3" penetration). Suppose there are 40 trusses which are attached with 6 nails each (3 each side). The entire roof weighs 24,000 pounds and the nails supply 31,000 pounds resistance to lift. The ceiling plus insulation add an extra bit of weight (roughly 10,000 pounds in this example). The question is what windspeed is required to lift a roof which has a total resistance to lift of 65,000 pounds spread over 2,000 sq. ft. (i.e., about 65,000 ÷ 2,000 = 32.5 psf). Thus, the upward pressure needed to overcome the roof's resistance to lift is 32.5 psf. Actual survey and test results indicate that in practice this figure can be nearly doubled because of corner clips and connections inside the house. But even with the additional resistance supplied by the internal connections, the windspeed required to lift the entire roof is only about 100 mph. Furthermore, the external walls in the vast majority of houses have almost no cross-strength without the support of trusses. Once the roof is lifted completely away from the structure, and the walls lose this support, they can easily flex, buckle and collapse.

The above sequence happens quite frequently in wind-related disasters. Obviously, to avoid this type of failure the roof-to-wall connection must be strengthened. Of the many methods available to do this, one of the most effective is the use of "hurricane clips" or steel connector plates. (Connector plates are small rectangular plates made of light gage, galvanized steel in which a dozen or more teeth have been punched. The plate is typically fastened to the boards by two or more nails per board, then the claw-like teeth are pounded into the wood. Forced removal of these plates requires tearing, or shearing, of the wood.) By properly selecting strong plates with deep claws, one can add upwards to 1800 pounds resistance per plate[6] (at a bulk cost in 1980 of approximately 25 cents apiece for the plates). The addition of 100 such plates around the perimeter of the roof could increase the resistable wind to 150-170 mph.

Again, let's suppose we've spent about $50 for components to reinforce both the roof decking and the roof-to-wall connnections as the home is built as discussed above. Are there any other structurally vulnerable spots? The answer is yes--one more primary failure point; namely, the foundation-to-wall connection. Some contractors, particularly where building codes are lax, anchor houses to foundations with nails driven through the wooden base plate into the green concrete with a power gun. However, test and survey results (referred to above) indicate that such structures can leave their foundations at wind speeds of 160-200 mph. On the other hand, such failures are minimized if anchor bolts are utilized. The cost of labor and materials for anchor bolts at 6 foot intervals around a 160 ft. perimeter is about $40 in 1980.

4. SUMMARY

With approximately one hundred dollars worth of additional material, a builder can structurally reinforce a medium-size home to sustain little or no serious structural damage even in very strong winds (up to about 150-170 mph) as indicated in Table III. As pointed out by Eagleman et al.[4] "Considering the cost of lumber, it is a tremendous waste of resources to build a structure when the material is not able to develop its rated capacity because of poorly constructed connections." An interesting report to this effect is presented by Minor et al[8] regarding damage created by the Lubbock, TX tornado. The study found that nearly all wood frame structures that were damaged had failed at the connections. Of course, as winds approach and exceed the speeds discussed above, other factors come into play such as impact or penetration by large, wind-driven missiles (debris). Potential for structural failures multiplies rapidly as the building is pummeled and pierced by large flying objects. But hurricane winds very rarely reach 170 mph and less than 2% of all tornadoes are this intense. Most actual property damage is done by winds at much lesser speeds (e.g., in the Lubbock storm most damage sustained by structures was caused by winds in the 75-125 mph range[8]). The bulk of this damage can readily be prevented. The primary reinforcements that should be made are:

1. Additional fasteners on the roof decking; sufficient to resist strong separation pressures;
2. Hurricane clips, or connector plates, to reinforce the roof-to-wall connection;

3. Anchor bolts to secure the structure to the foundation ;

A few other suggestions which are discussed in some of the literature referenced in this article include:

4. Angling the roof a bit more. Wind loadings decrease as the roof angle increases up to an angle of about 45°; a 45° roof (for the gabled variety) provided the least wind loading of all the roofs tested in reference (4), however hip and mansard roofs appear to offer better resistance to wind[2]. It should also be mentioned that steeper roofs are less susceptible to snow loading for homes built in cold country ;
5. The use of WELL ANCHORED dormers or other irregularities in roof line appears to break up the wind and reduce peak loadings although shingle damage potential is slightly greater near such irregularities ;
6. Effective corner bracing at the junction of exterior walls and diagonal wind braces on the framing face can add appreciable strength to the exterior walls should the roof disengage. A few connector plates along the junction of the base plate and framing stud can also help strengthen free-standing walls ;
7. Venting the roof helps to lower internal pressure potential and eases the effect of separation pressures on the roof decking. The loading on the roof, rear wall and at least two side walls is reduced. Even though increased loading results on the upwind side of the house, the external walls should remain intact as long as the roof does (except for possible damage by missiles).

ACKNOWLEDGEMENT

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TABLE I

WINDSPEED VS. WINDWARD WALL PRESSURE (ALSO LOWER LIMIT VALUES FOR SEPARATION PRESSURE).

Windspeed (MPH)	25	35	50	75	100	125	135	150	175	185	200
Pressure (psf)	1.3	2.5	5.1	11.5	20.5	32.0	37.4	46.1	62.8	70.2	82.0

TABLE II

WINDSPEED VS. APPROXIMATE COMBINED UPWARD PRESSURE ON WINDWARD EAVES (FOR FLOW PERPENDICULAR TO EAVE).

Windspeed (MPH)	25	35	50	75	100	125	135	150	175	185	200
Pressure* (psf)	4.2	8.1	16.6	37.4	66.6	104.0	121.6	150.0	204.1	220.2	266.5

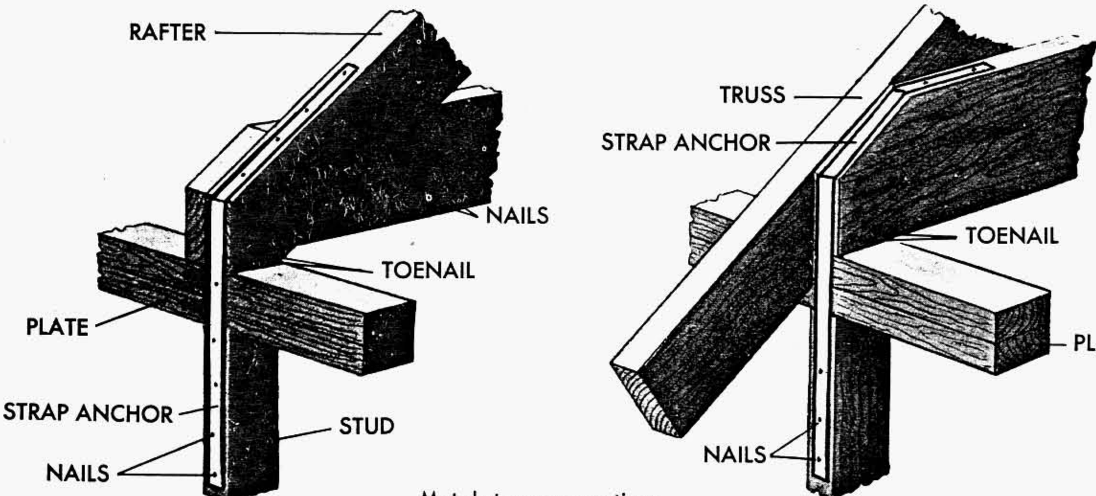
*Composed of windward wall pressure (P), .75P for aerodynamic effect and 1.5P estimated separation pressure.

Table III

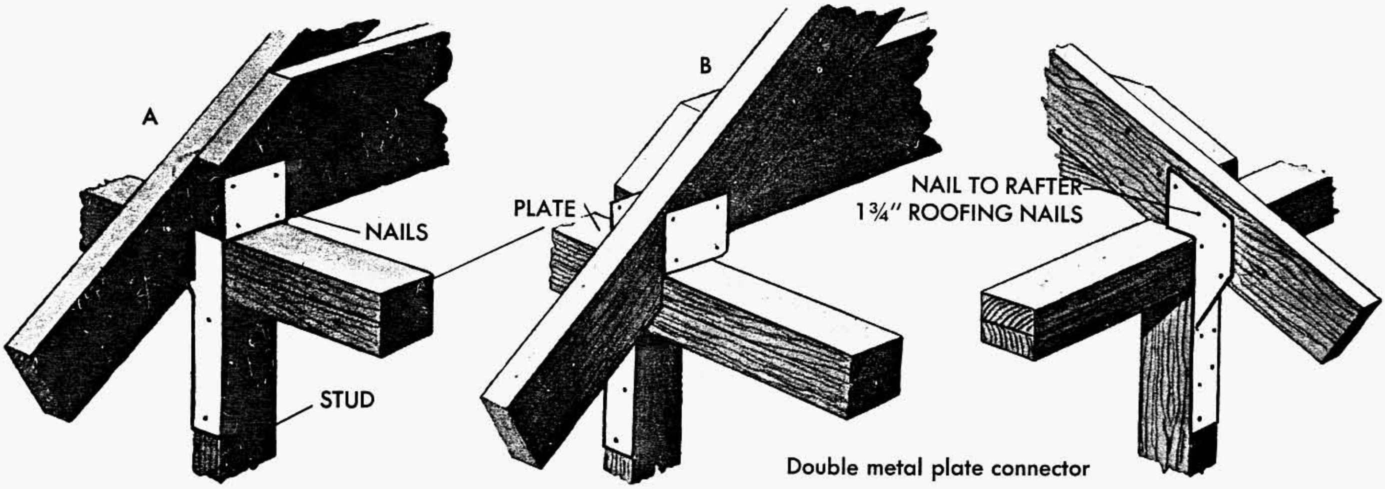
DAMAGING WINDS

WIND SPEED MPH	RESULTING DAMAGE
1. 75-90	1. Shingles, loose decking components
2. 100-110	2. Decking without soffits
3. 110-125	3. Non-reinforced decking, toe nailed roofs
4. 150-170	4. Reinforced decking, roofs with deluxe "hurricane clips," non-anchored homes shift off foundations

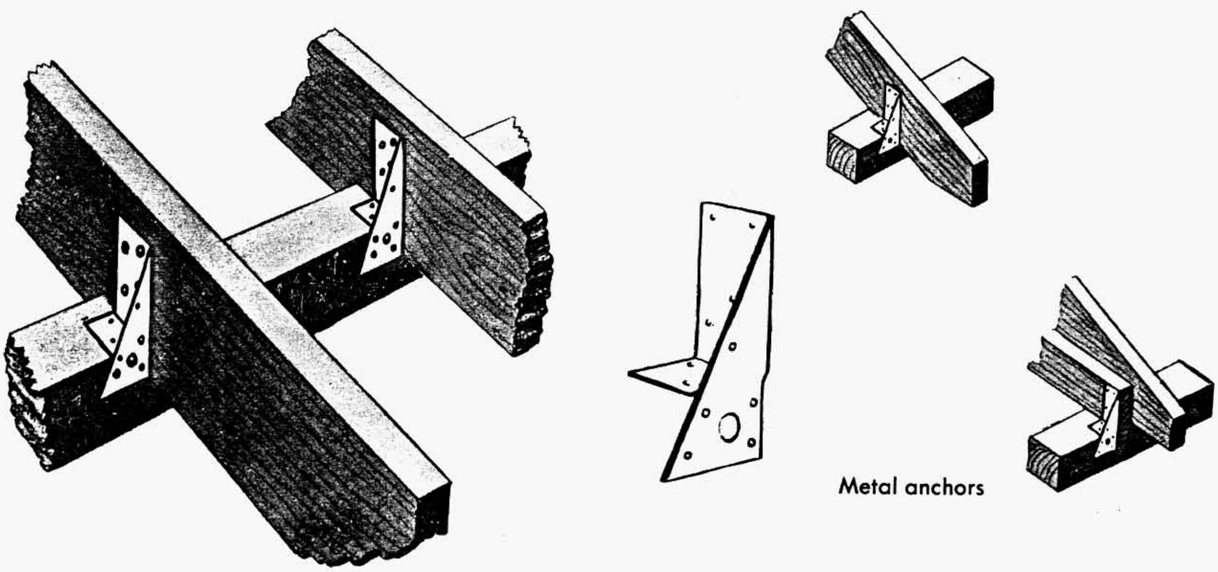
ANCHORAGE OF ROOF SYSTEM TO TOP PLATE



Metal strap connections



Double metal plate connector



Metal anchors