PERFORMANCE OF ROOFING SYSTEMS IN WIND STORMS

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INTRODUCTION

Structural engineers from Texas Tech University's Institute for Disaster Research have visited the damage sites of 28 windstorms that have occurred since 1970 [1, 2, 3, 4]. Exploiting these unique opportunities to study the effects of winds on roofing systems, the investigators have divided roofing system failures into four general types, relating these classic failure types to wind pressures acting on roofs during windstorms.

In the first part of this paper I discuss wind pressure patterns on buildings. I also discuss the hazard presented to glass windows by windborne roof gravel. The discussion of wind effects on building roofs is based upon analysis of wind loads in several current building codes and standards [7, 8, 9]. The second part of the paper includes pictorial examples of roofing failures and failures to nearby glass panels caused by wind effects. Each of the four general types of roofing system failure and the hazard to glass are discussed and illustrated.

WIND EFFECTS ON ROOFING SYSTEMS

As windstorm airflow passes over a building's roof, several wind-structure interaction phenomena take place. If the roof is essentially flat, the pattern of air flow over the roof tends to lift the roof as a unit. This well known Bernoulli phenomenon lowers pressure within the rapidly moving air over the roof's surface. Secondly, localized "separations" of air flow along eaves, ridgelines and at roof corners produce fluctuating "pockets" of low pressure downstream from air flow separation points. These low-pressure pockets can exert high uplift forces across roof components, and introduce the possibility of fatigue failure in certain types of roofing material. Associated with these two basic phenomena are additional uplift pressures than can be added to the above pressures, if there is a roof overhang or if a windward wall component fails (or is left open), permitting internal pressure to build within the building. Both of these latter situations serve to compound the upward acting pressure differential across roof components.

A second hazardous effect concerns scour or "blow-off" of loose roof gravel during windstorms. Removal of substantial quantities of roof gravel attaining velocities sufficient to break window glass has been documented during windstorms [10, 11]. These two phenomena—airflow-induced pressures and scour of roof gravel—are discussed in greater detail below.

1. Air Flow Induced Pressure - Wind pressures on buildings are discussed in several references [12, 13, 14]. The uplift pressure coefficient (C_p) for a roof component relates pressure change to a reference value called the stagnation pressure [15]. A pressure coefficient of 1.0 for a roof component, for example, would mean that the roof component will experience a change in pressure equal to 1.0 times the stagnation pressure, for a given wind velocity. The familiar equation for stagnation pressure is $q = 0.00256\ V^2$, where V is wind velocity in mph and q is stagnation pressure in psf. Pressure coefficients associated with roof components are usually assigned a negative sign, indicating uplift.

Figure 1 illustrates pressure coefficient values for several common roof conditions. For a flat roof, overall pressure coefficients of - 0.7 are common. Slightly sloping roofs may experience overall pressure coefficients of - 1.0. "Pockets" of low pressure along eaves and ridgelines caused by air flow separations may produce pressure coefficients up to - 2.4 (note that, in this context, an "eave" need not have an "overhang"). The most severe pressure coefficients identified with roofing systems occur at roof corners, with values up to -3.0 to -5.0 set by some building codes and standards [7, 8, 9]. These values accompany certain angles of incidence as wind blows into the corner of building.

Figure 2 illustrates factors that may compound uplift pressures. Internal pressure induced underneath a roof when a windward wall or wall component (window or door) fails can produce an internal pressure coefficient of - 0.8. This value can combine with the - 0.7 or - 1.0 value for overall pressure reported above to produce net pressure coefficients across the roof of -1.5 to -1.8. Roofs with overhangs (overhanging eaves) invite the development of pressure underneath, again with values as high as -0.8. Here, combined values of -0.8 and values approaching the -2.4 value reported above near flow-separation points can produce extremely large net pressures across overhanging roof components.

2. **Scour of Roof Gravel**

Windblown gravel can damage glass, as documented in reference [5]. Theoretical studies [10] indicate that wind velocities in the 80-100 mph range can "blow-off" gravel at speeds fast enough to break window glass, and wind-tunnel tests have confirmed these general conclusions [16, 17]. For example, a 0.61 gm rock (statistically average size) and a 5.55 gm rock can attain velocities of 68 fps and 50 fps, respectively, in a 100 mph windstorm, if an acceleration distance of 50 ft is available. Table 1 contains impact velocities that will break common window glass for these same rock sizes.

TABLE I. MISSILE IMPACT VELOCITIES (ft/sec) THAT WILL BREAK WINDOW GLASS

	GLASS TYPE				
Missile Weight	Sheet 3/32 in.	Plate 1/4 in.	Float 1/2 in.	Float 3/4 in.	Tempered 1/4 in.
0.61 gm	63.6*	56.2	— —	— —	71.5
5.55 gm	44.9	37.4	38.5	57.1	54.4

*all values are mean minimum breakage velocities in feet per second (fps)

There are several methods of preventing gravel blowoff. Parapets of various heights and geometries can retain loose gravel on the roof, while also reducing uplift coefficients [9, 17]. Anchoring or removal of loose stones is another, less reliable method.

EXAMPLES OF ROOF FAILURES

Currently on file at Texas Tech University, records of 28 separate windstorm events - tornadoes, hurricanes, cyclones, thunderstorms, mesocyclones—contain examples of several kinds of roofing system failures, classified as follows:

- peeling failures
- panel failures
- supporting member failures
- system failures

1. **Peeling Failures**

The locally severe, uplift pressures identified with roof corners, ridgelines, and eaves often initiate peeling of roofing materials in windstorms. Figure 3 illustrates this type of failure. Figure 3a shows the effects of peeling from roof corners, eaves, and ridgelines. For a close-up view of the roof corner, see Fig. 3b right-center portion. The failure started with the roofing material at this relatively high pressure point (Ref. Fig 1) and eventually included uplift of roof panels.

2. **Panel Failures**

The second potential weak link in a roofing system is the connection between roof panels and roof supporting frame. Examples of this type of failure are found in metal buildings (Ref. Fig. 4a) where metal panel to purlin connections become important. In commercial construction, connections between roof panels and open web steel joists (foreground of Fig. 4b) or other types of roof framing system (background of Fig. 4b) often become critical.

The design concept in which roofing failure is permitted as a means of protecting the principal framework of a building is often considered by structural engineers, particularly those who deal with tornado-resistant design. While this design approach may apply to some types of buildings (such as certain industrial buildings), it is inappropriate in many situations. First, the contents of most buildings are too valuable to sacrifice in favor of protecting the principal framework. Secondly, the contribution to windborne debris which may result from using this design concept has technical, as well as legal, implications.

3. **Supporting Member Failure**

Purlins or other members supporting roof system components must be designed to resist wind pressures shown in Figures 1 and 2. Failure to consider net uplift pressures may cause normally tension-resisting components to resist compression. Such stress reversal buckled the lower chord of the open web steel joist shown in Figure 5. Net uplift pressures induced through the internal pressure mechanism (Ref. Fig. 2) reversed the joist's normal gravity load pattern, stressing the top chord in tension, the bottom chord in compression. The purlins in the end span of the metal building illustrated in Figure 5b also buckled upward. In this example, air flow over the building (from left to right in the photograph) induced uplift on the roof through the mechanisms illustrated in Figure 1. The purlins' unbraced lower flanges buckled laterally under compressive forces.

4. System Failures

When total uplift pressures acting on overall roofing systems exceed roofing system-to-wall connection strength, system failures may occur. Two examples of this type of failure are offered in Figure 6. In Figure 6a, an open web steel joist roofing system failed at joist-to-wall connection points. In Fibure 6b, prestressed, "double T" beams were lifted from their supports by upward-acting pressures. Here, total pressures across the roofing system, which occurred through combined wind actions illustrated in Figure 2, were sufficient to cause roofing system failure.

EXAMPLES OF ROOF GRAVEL HAZARDS

Many roofs containing loose gravel are located in areas where they present a hazard to glass windows and glass spandrel units in adjacent buildings. An example of loose roof gravel menacing a glass-clad building is presented in Figure 7. Evidence of missile impacts on glass panels is presented in Figure 8. The glass panels to the left and right of the center panel in Figure 8 were broken, and have been replaced with new glass; the center panel sustained missile impact damage, but did not fall out of the frame.

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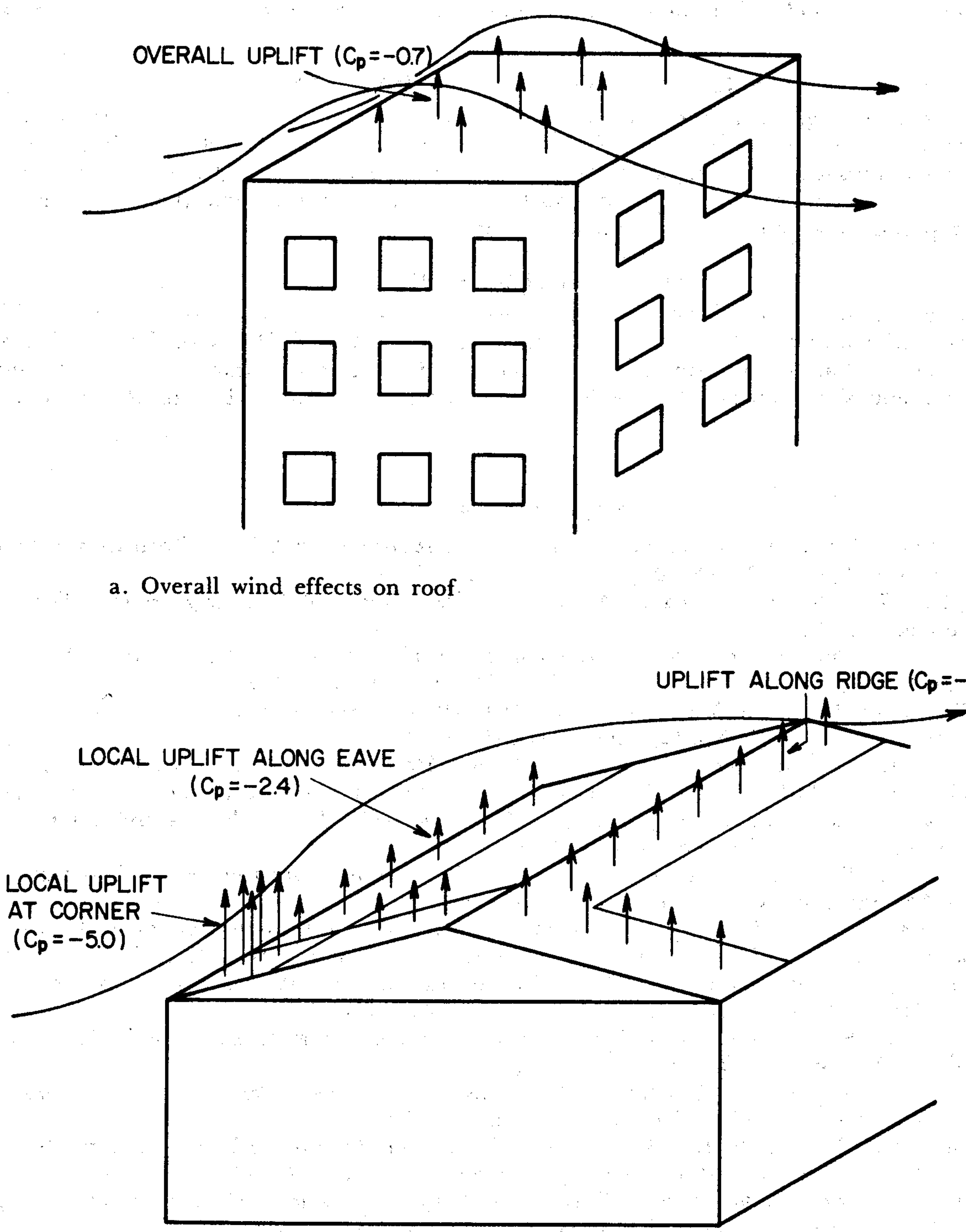
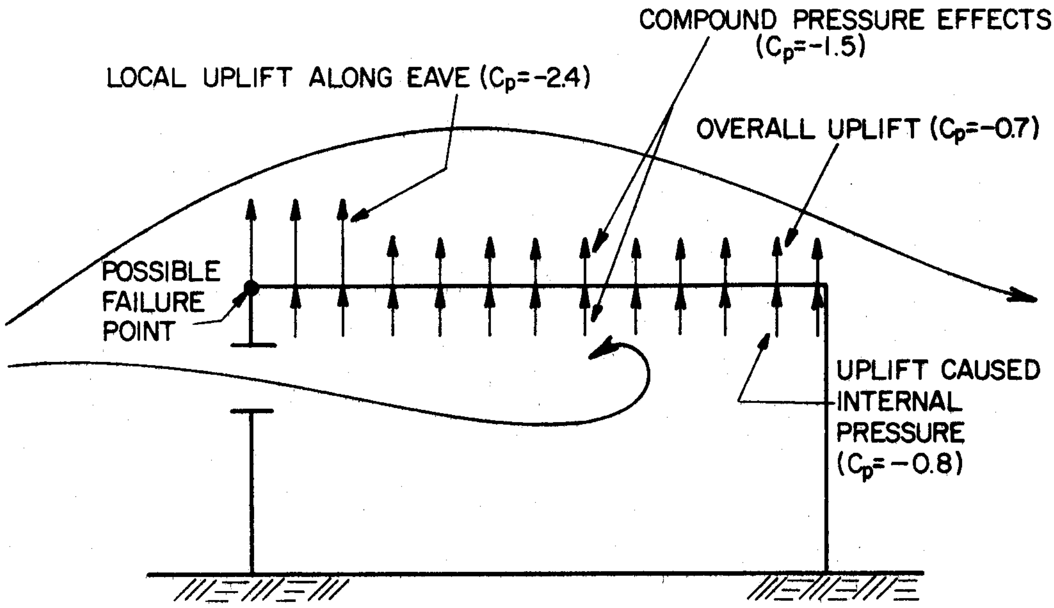


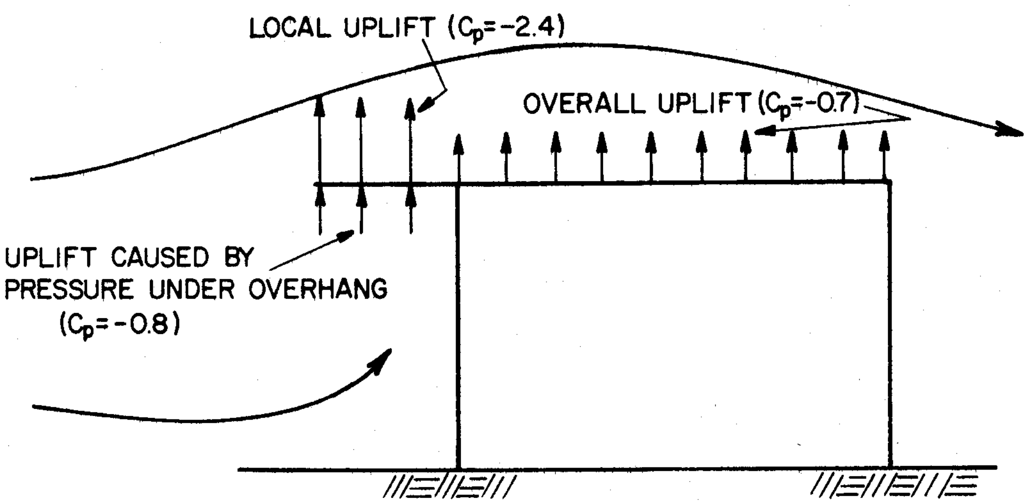
a. Overall wind effects on roof

b. Local wind effects on roof

FIGURE 1-WIND EFFECTS ON ROOFING SYSTEMS



a. Effects of internal pressure



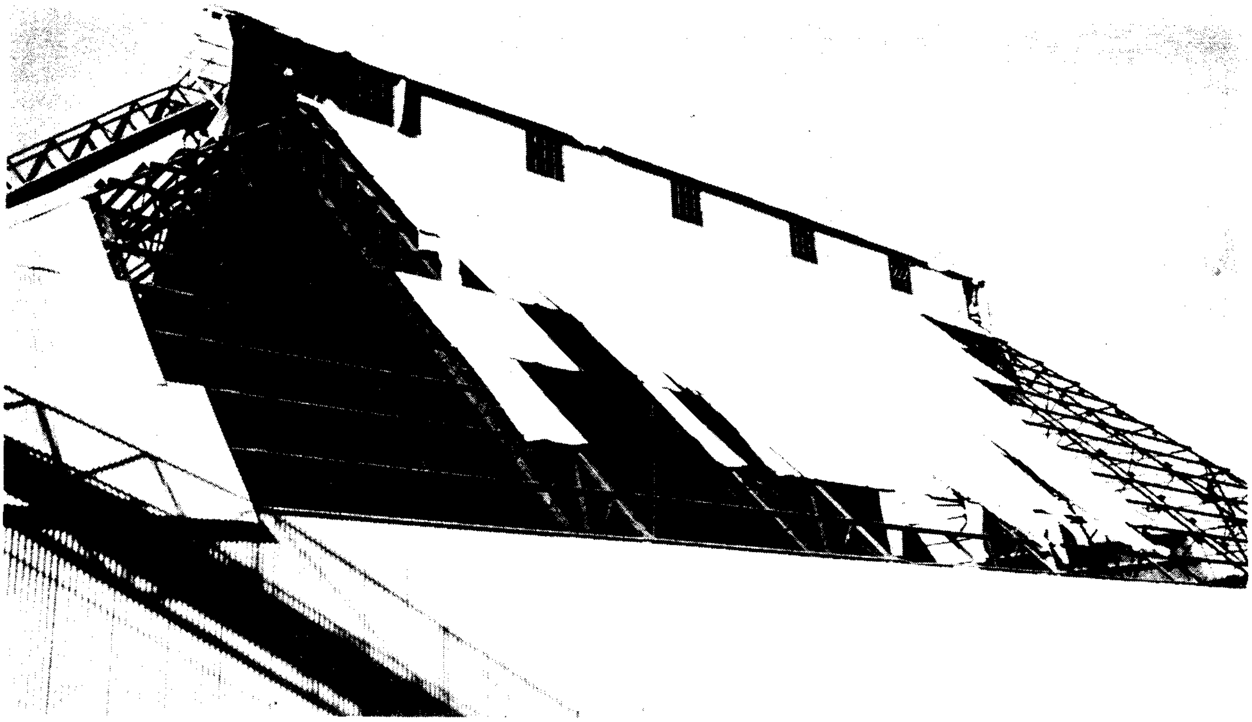
b. Effects of pressure under overhangs

FIGURE 2–TWO PHENOMENA WHICH ADD TO WIND EFFECTS ON ROOFING SYSTEMS

a. Relatively large pressures at roof corners, eaves, and ridges often initiate peeling types of failures

b. Roof corners are especially susceptible to peeling failures

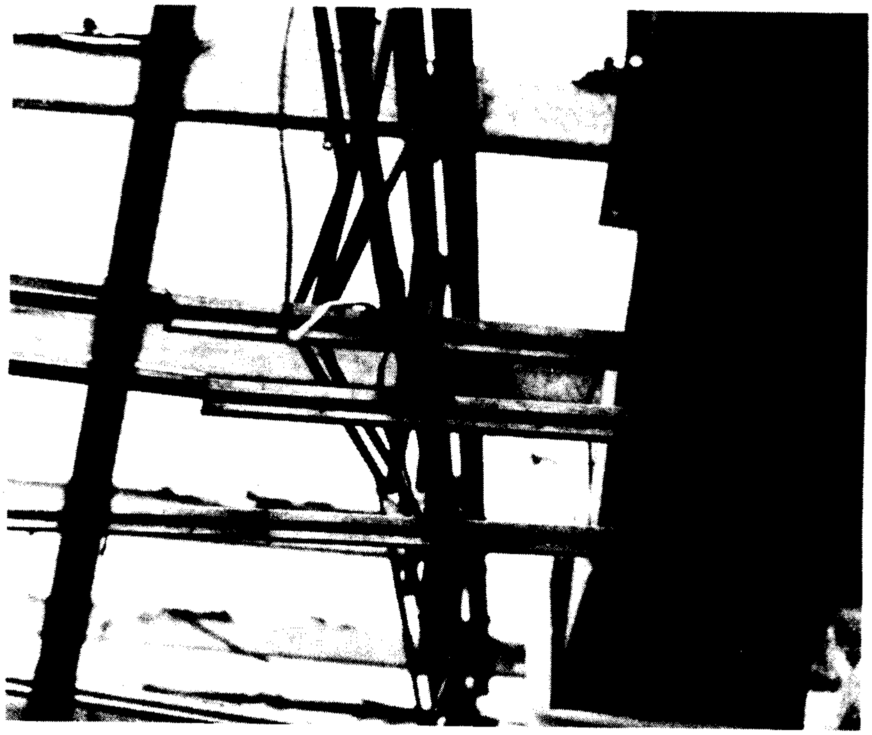
FIGURE 3—PEELING FAILURES



a. Connections between panels and purlins in metal building systems can present failure initiation points.

b. Panel to joist or other framing member connections sometimes represent the weak link in the roofing system.

FIGURE 4 — PANEL FAILURES



a. Bottom chord of open web steel joist buckled laterally as a result of net uplift pressures on the roof.

b. Purlins in the end span of this metal building buckled upward through actions induced by uplift pressures.

FIGURE 5 – SUPPORTING MEMBER FAILURES

a. Failure of this roofing system initiated in the roof-to-wall connection detail.

b. Large uplift pressures can cause system failures of concrete roofs.

FIGURE 6 —SYSTEM FAILURES

FIGURE 7 — LOOSE ROOF GRAVEL PRESENTS A HAZARD TO ADJACENT GLASS WINDOWS

FIGURE 8 — EVIDENCE OF MISSILE IMPACTS ON GLASS WINDOWS NEAR GRAVEL SURFACED ROOFS