Chapter 4 explains that flange bracing is ordinarily used to improve the efficiency of the frame rafters under the loading conditions that place their bottom flanges in compression. But flange bracing installed only on one side of the frame can become a liability under heavy snow accumulation: the sagging purlins push on the kicker angles and laterally displace the bottom flange of the frame (Fig. 10.19*a*). As a result, the frame receives an added torsional loading. Since the frame could already be fully loaded by the severe snowfall, any unanticipated torsion may potentially lead to its overstress and failure. Once that happens, the whole building can collapse—if the loading is severe enough. (To avoid the added torsion, flange bracing should be installed on both sides of the frame, as in Fig. 10.19*b,* so that the forces from the sagging purlins on two sides partly or fully cancel one another.)

This failure scenario goes against the desire of many modern building codes to avoid progressive collapse of buildings. In a progressive collapse, a few or even a single overloaded or damaged structural element brings down the whole structure. As ASCE 7[13] puts it:

> Buildings and other structures shall be designed to sustain local damage with the structural system as a whole remaining stable and not being damaged to an extent disproportionate to the original local damage.

In one model for the progressive collapse of metal buildings, suggested by Murtha-Smith et al.,[14] failure starts with a few overloaded purlins, perhaps in the end spans, which fail and undergo large

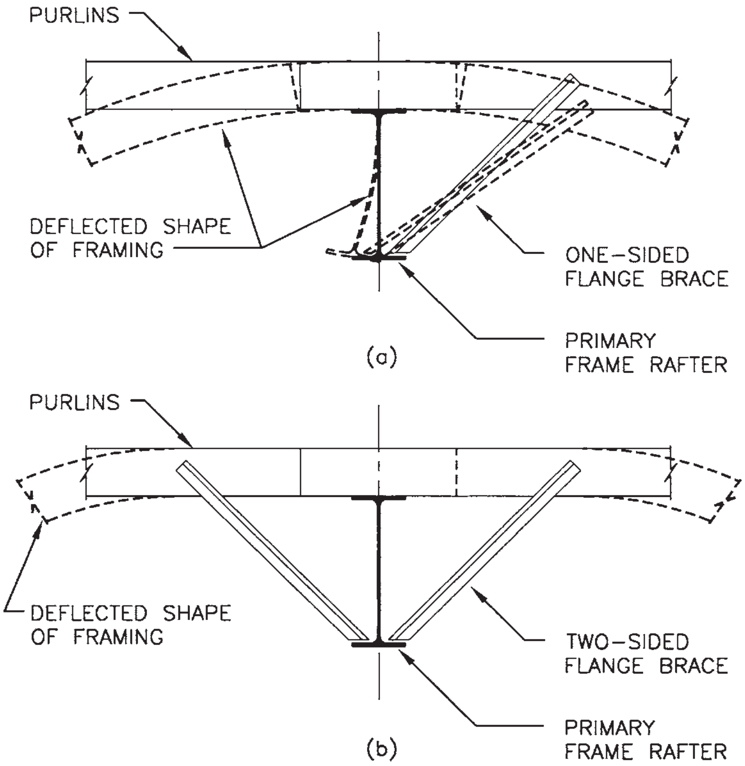

FIGURE 10.19 The number of primary-frame flange braces affects frame stability under heavy load: (*a*) brace on one side displaces the bottom flange of frame when purlins sag; (*b*) braces on both sides balance the opposing forces from sagging purlins.

deflections. Following that, metal roofing gets stretched in the shape of a catenary and pulls on the adjacent purlins with a tremendous force they are unable to resist. As a result, purlins in the adjacent bays rotate and fail as well. If the single-side flange bracing is present, the sagging purlins push out the bottom flanges of the rafters, as just discussed. The rafters twist and fail, pulling the exterior columns and walls inward. Since the purlins in one bay are bolted to those in the adjacent bays, purlin failure propagates throughout the building. The author's experience with investigation of metal building collapses is consistent with this model.

Another suspected mode of failure in cold regions involves water freezing in the purlin-supported gutters. The resulting overload of the first one or two purlins causes their rotation into a near-horizontal position. The roofing then pulls on the rest of the roof purlins, which also "lay over" and fail. A proper eave and ridge bracing assembly, illustrated in Chap. 5, can help prevent this type of progressive collapse.

The insurance industry is well aware of the fact that some metal buildings can fail very quickly under a major snow overload. Such failures occurred in March 1993 in northwest Georgia and in 1994 in eastern Pennsylvania. A magazine published by Factory Mutual notes that "metal building systems fared the worst in the Storm of '93, perhaps because of their design.… When a collapse occurs, it usually is total."[15] One building in Pennsylvania reportedly collapsed in 10 seconds, start to finish. Again, the apparent cause of that failure was a sheer amount of snowfall.

These observations are supported by the statistics cited in Sec. 10.9.1[16] and by other sources. For example, a recent discussion among the representatives of structural engineering organizations in 14 states, as reported in the *Structure* magazine,[17] asked a question: "In recent snow storms, what types of construction seem to have suffered the most distress?" The answer was: "The vast majority of responses pointed to plated wood truss roof structures and low-rise metal building systems." Most of the respondents "felt that the actual loads were consistent with code-mandated design loads and acceptable safety factors." The most common causes of these failures? "[I]mproper installation, improper detailing, inadequate bracing, web buckling, lack of roll over prevention at supports, and not accounting for unbalanced loads on continuous members." Another frequent response was not accounting for snow drift. The observations made by experienced practitioners from around the country parallel those found in this book.

What about wind damage? The damage from hurricanes may be local, as in Fig. 10.18, or involve a failure of the whole building. As a result of widespread building damage after Hurricane Andrew (August 24, 1992), the wind-resisting provisions of the South Florida Building Code—already the toughest hurricane code in the nation at the time—were further strengthened. Saffir[18] states that some of the new requirements for pre-engineered buildings included banning the use of cables for tension members (consistent with our suggestions in Chap. 3), using the metal siding with a minimum thickness of 24 gage and reducing its allowable deflection criteria, and anchoring the doors to the building frame.

After Hurricane Iniki had hit the Hawaiian Islands in September 1992, the Structural Engineers Association of Hawaii prepared a damage survey. The survey found that, along with residential structures, some pre-engineered buildings had been affected. Among the report's conclusions: "Pre-engineered metal buildings appeared to have proportionally more damage than other types of engineered structures."[19] Again, collapse of some buildings was total (Fig. 10.20).

The troubling aspect of such metal building failures is not that some of the buildings were overloaded—this can happen to any structure—but that there was so little ductility and reserve strength when the overload came. The reports about building failures under the loads which were less than the design values are especially disconcerting. In general, however, properly designed metal building systems should provide safe and sound shelter that can withstand all code-mandated structural loads without undue deformations. It should also be noted that metal building systems have a good record of resisting earthquakes. The troubles are likely to occur not in well-engineered metal building systems but in structures put together from metal building components without proper engineering.

10.9.8 Failures Caused by Construction Deficiencies

Some failures have been traced to improper construction techniques. As shown in Chap. 16, collapse can occur at the very beginning of metal building construction—the primary frame erection—if the