Learning from failures I

STEP lecture E27
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Objective
To describe some structural failures caused by snow, wind or landslide.

Summary
Structural failures caused by wind, snow and landslides are discussed. The wind and snow failures are mostly due to mistakes in design or manufacture. The behaviour of the houses in the landslide shows that a "stiff" wood frame house can withstand a very severe load condition and yet hold together. Proper design with accurate design loads results in buildings that can withstand severe load combinations very well.

Storm damage

General
Some damage cases from the heavy storms that occurred in West Sweden, in September 1969, are described. It happened a long time ago, but many of the experiences are still as relevant as they were 25 years ago. The damage was investigated and the results were given in a report (Johansson 1970). Many general observations are valid for all types of structures. Many of the roofs that blew off were just lying loose on top of the houses, they were not fixed to the main structure at all. In several cases the main reason was so obvious that no further extensive investigation was needed.

The wind velocities were high, the maximum 10 min mean velocity recorded was 31 *m/s* and the maximum gust velocity recorded was 37 *m/s*. Compared with earlier and later storms, the storms of 1967 and 1969 passed over areas with big cities and they lasted for a long time. For about 4 hours around noon, the wind velocity was at its maximum value or was very close to it.

Many of the damaged houses were quite newly built, most of them were less than ten years old.

Timber roof structure on a concrete slab
There were quite a lot of two or three storey houses that lost their roofs. On the upper concrete slab a timber frame system was built with vertical posts 50 x 100 *mm* and rafters 50 x 100 *mm* to 50 x 150 *mm*. The spacing of posts and frames was dependent on the house and rafter dimensions, however the frame spacing was very often 1,2 *m*. A typical sketch of the structure is shown in Figure 1.

All of the examined damage had either insufficient or non-existent anchorage of the timber structure to the concrete slab. In many cases the roof structure was attached at the eaves, but none of the posts was fixed in any way. This means that when the storm succeeded in breaking the anchorage at the eaves the whole roof was free to blow off. Then the wind force could also influence the roof plate with pressure from below, see Figure 2.

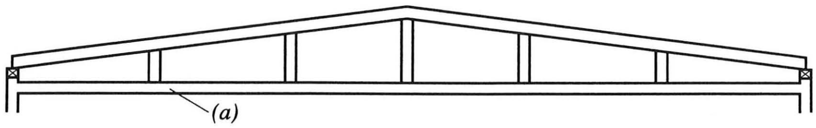


Figure 1 *Typical sketch of a timber roof structure on a concrete slab; (a) concrete.*

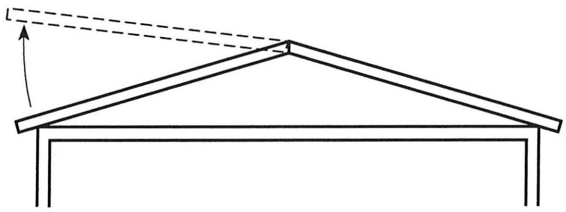


Figure 2 *Probable damage sequence.*

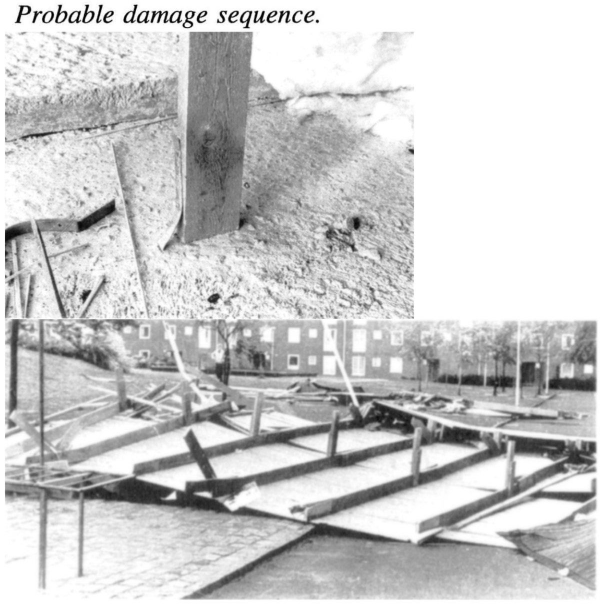


Figure 3/4 *Damage examples. Fixing of post to the roof slab. Note the wrong position of the steel strap (left). Part of the roof is lying on the leeward side of the damaged building (right).*

Different types of anchorage were used. The most common was thin steel straps, cast in the slab and nailed to the timber structure. In other cases a horizontal 50 x 100 *mm* timber was bolted to the concrete slab, to which the timber structure was fixed with just a few nails. However, many of the anchorages showed very poor workmanship and could not be expected to resist the wind forces. In Figures 3 to 6 some examples of damage are shown.

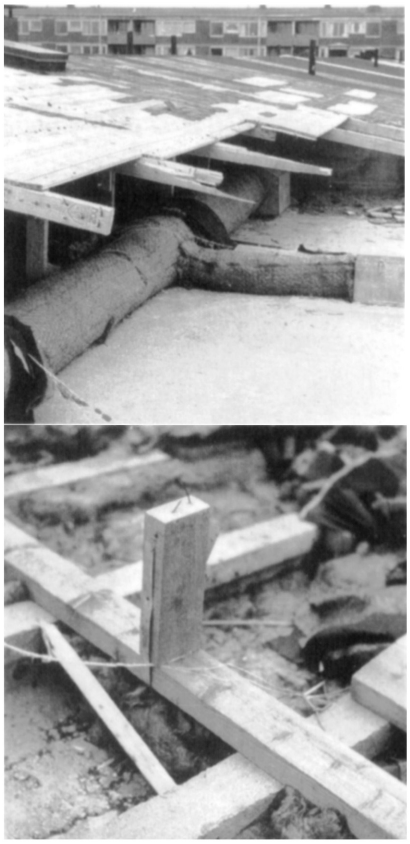


Figure 5/6 *Part of a damaged roof (top). Fixing of the posts to the secondary member laid on the concrete slab (bottom).*

Temporary timber frame building

A temporary timber building was totally destroyed during the storm. The building was 30 x 15 *m* in plan and 5,2 *m* high at the ridge. The frame system can be seen in Figure 7. All the joints in the structure were bolted. Unfortunately the size of the timber used is unknown but the rafters were approximately 50 x 150 *mm*. The purlins were fixed to the frame rafters with a supporting wood block. Each block was nailed with three nails to the rafter. The purlin, however, was only nailed with one nail to the block. Because of this the whole roof blew off. The frames were sway deformed with a maximum deflection of 0,5 *m*. If the roof had not been removed, the frames would have probably been broken instead.

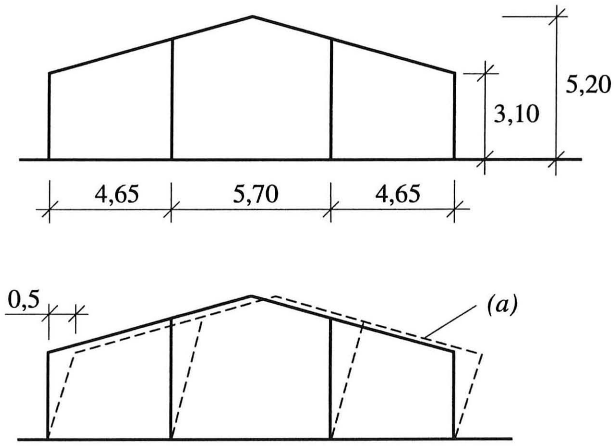


Figure 7 *The frame structure and the deformation of the frame; (a) deformed frame.*

Figure 8 *View of the damaged building. A blown-off roof section can be seen to the left.*

Snow load damage

General

During the winter of 1976/1977 heavy snow loads caused several structural failures in Sweden. The damage was of different types, ranging from failures in roof membranes caused by freezing water to total collapse of a building. In an investigation, (Johannesson and Johansson 1979a) almost one hundred different damaged structures were studied. The investigation included steel, timber and concrete structures.

The snow depth during the winter, measured by the Swedish Meteorological and Hydrological Institute (SMHI), was in some cases found to considerably exceed the 50 year Mean Recurrence Interval (MRI) ground snow.

Causes of snow damage to timber structures

The main reason for the structural failures was the heavy snow loads causing the total load to exceed the load carrying capacity of the structures.

Excessive snow loads - that is the amount by which snow loads exceeded the snow loads given by the Swedish Building Code, drifting snow and sliding snow were estimated to have caused about 30% of the failures in the timber structures. Manufacturing faults, including all types of deviations from the prescribed design, both in factory and on site, and also underdesign, that is mistakes made either in calculations or as an inappropriate design, were estimated to be the cause in about 65% of the failures.

Some typical failures

Bad gluing of wooden structures had caused failures in glulam beams and plywood webbed I-beams. The glulam beams were of an I-type where the gluing of the flanges to the web was badly done. Due to the thickness of the flanges it was probably impossible to achieve proper pressure along the whole gluelines during manufacture. One of the basic conditions for successful gluing is that the glued surfaces are plane enough to come in close contact and that the applied pressure is sufficiently high. Especially in the case of nail-gluing it is necessary to use planed surfaces. The plywood beams failed due to badly planed flanges resulting in bad glue joints.

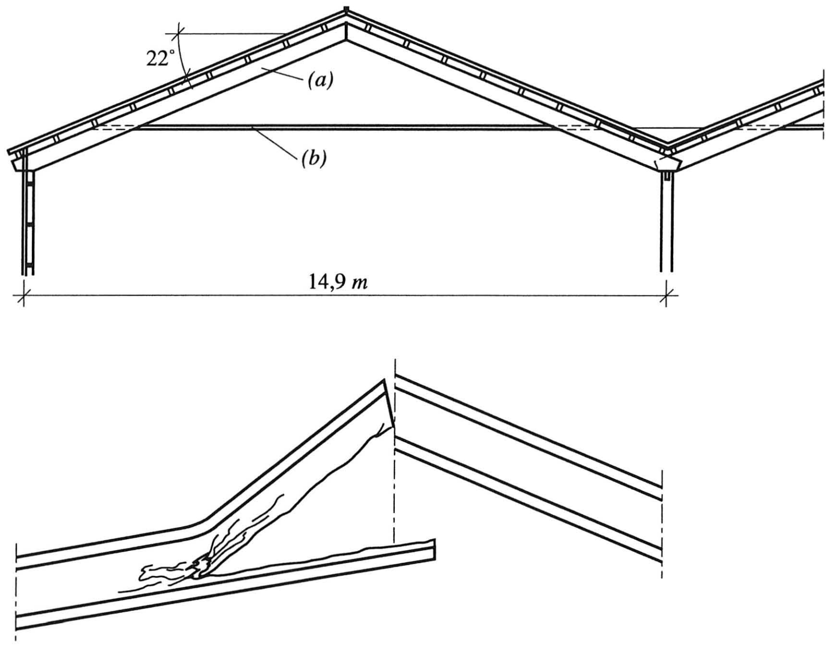


Figure 9 *Failure in a glued laminated timber structure due to bad gluing. Section (top) and sketch of the failure (bottom); (a) glulam, (b) tension bar.*

Timber connections with nail plates (punched metal plates) are sensitive to misplacement of the nail plates since the plate size is often small. Collapses of roof trusses were found to be due to undersized nail plates at the supports. These small plates were placed so that cracks could develop in the rafter leading to a collapse. When nail plates are used it is necessary not only to determine the minimum size of the plate from strength considerations but also to take into consideration the possibility of crack development. A similar failure occurred in a glued laminated beam with a notch at the support.

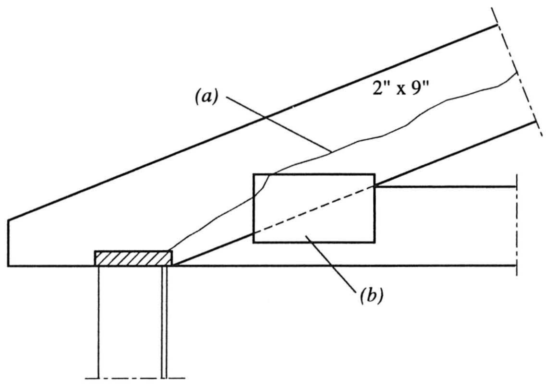


Figure 10 *Joint with a nail plate that is too small; (a) failure surface, (b) nail plate.*

The design of carports usually means rather limited resistance to withstand horizontal loads. In some observed cases the carports were built next to the neighbour's house to which, due to legal difficulties, they could not be attached. Sliding snow from that house caused horizontal forces in the carports resulting in permanent horizontal sway. Methods to prevent this kind of damage probably have to concentrate on preventing the snow from sliding, since it is difficult to stiffen a carport, due to its function.

Figure 11 Typical placing of a carport next to the neighbour's house.

Figure 12 shows one type of roof truss that is easily "overloaded". The moment distribution is very much dependent on the distance *a* in the figure. The failure is often a pure bending in section 1 or in the joint 2. In the case shown the bending stress in section 1 was calculated to 66 N/mm^2.

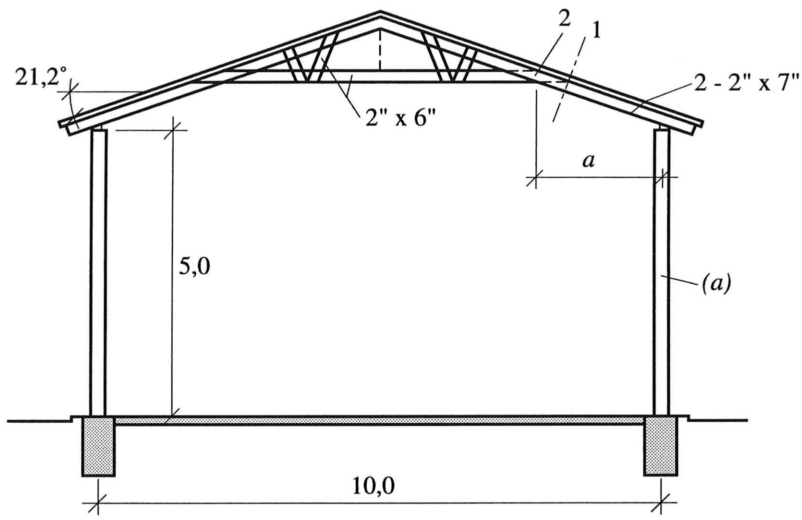


Figure 12 Section through a timber store house; (a) round timber pole.

Special failures

The primary structure of a cold store house was a three-hinged wooden truss frame. After about 20 years of service the building was moved to another place. A drawing of one half of the truss is shown in Figure 13. The flanges of the truss-beam were made of 50 x 125 *mm* sections. The contractor cut the frames in the sections A-A (Figure 13) when the building was moved to its new place. In these joints lap splices of 50 x 125 *mm* were nailed with just a few nails to each part. The length of the lap splices was about one metre.

The whole building collapsed due to failure in the joints A-A. This was probably a progressive failure starting from one frame. At failure the snow load was estimated at 1,1 kN/m^2 based on in-situ measurements. According to the Swedish Building Code the joint in the tension flange should have been nailed with about 130 nails. The estimated number of nails actually used in the joint corresponded to an allowable load of 0,2 kN/m^2 which is less than the dead load of 0,3 kN/m^2.

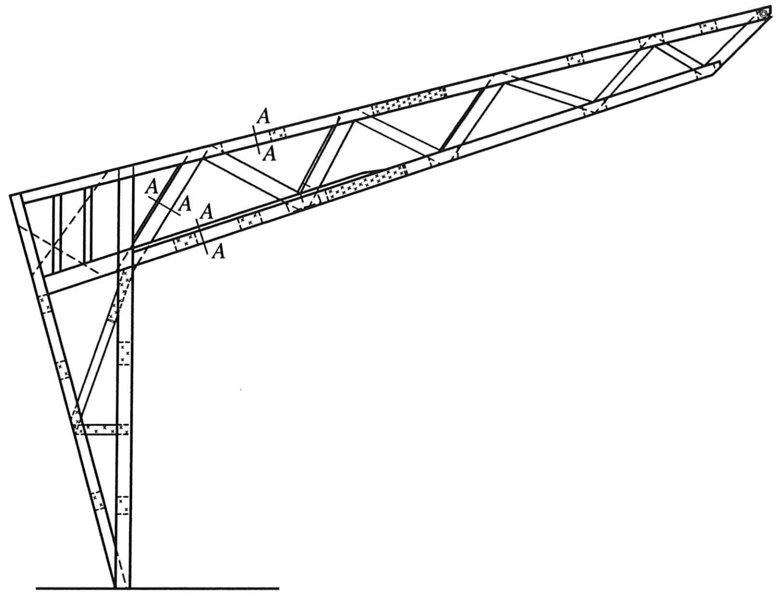


Figure 13 *One half of a three-hinged truss frame, spanning 15,5 m, with joints at A-A.*

The structure in Figure 14 probably collapsed due to the fact that the deformation in the steel wire tie rod was neglected. The failure occurred between joints B and C. The load on the structure was a combination of wet snow and wind forces. The snow load was approximately 1 kN/m^2 unevenly distributed on the roof. Stresses calculated for this load and wind load at a wind speed of 15 m/s gave a bending stress of 20 N/mm^2 if the deformation in the steel wire was considered and 4 N/mm^2 if not.

Hence it may be concluded that it is vital that the theoretical model in the calculations is correct in order to avoid a disastrous failure.

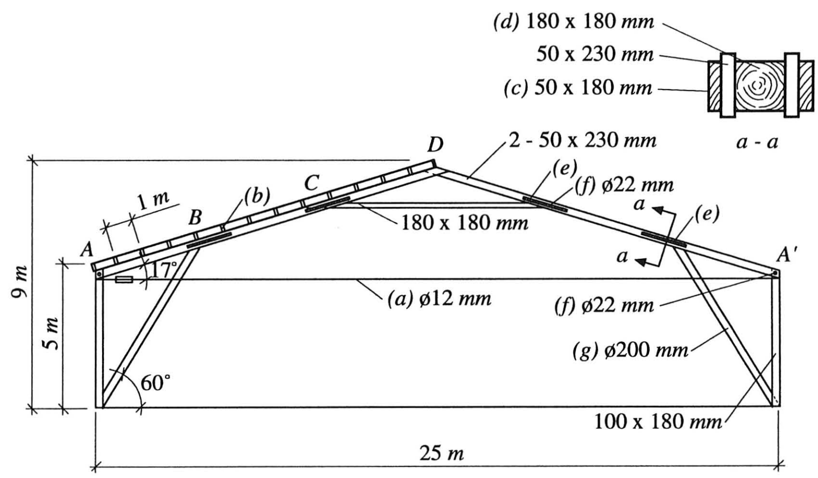


Figure 14 *Timber frame structure with a steel tension rod. (a) steel cable, (b) purlins, (c) cover plate, (d) distance piece, (e) splice, (f) bolt, (g) round timber.*

The landslide at Tuve

General
The slide area was about 27 hectares with a maximum length of 750 *m*. The slide width in the area where most of the houses were situated, was about 200 *m*. The number of houses in the landslide was 65 and about 100 houses close to the slide area were evacuated. Most of the houses moved about 100 *m* horizontally and 10 *m* vertically. The maximum transportation of any of the houses was 180 *m*. In Figure 15 a map of the slide area is shown. The map also shows the house slide paths.

The houses in the slide were of different types. Most of them were timber houses of different types - old houses (50 years or more), new houses with prefabricated elements and new houses with timber frames. Some of the houses had timber floor structures, but most of them had cast concrete floors, constructed of lightweight concrete or normal concrete elements. A few of the houses were built with brick or light weight concrete walls and concrete slabs. The most damaged houses were those built of lightweight concrete blocks. Those walls could not withstand the forces from the landslide.

The terrace houses at Almhöjdsvägen
The main reason for the severe damage to these houses was that the concrete walls in the basement broke down. The walls had very little or no reinforcement and they split at the corners. Then the concrete slab slid off the walls and broke. The basement walls were intact in only two of 29 houses. After the concrete slab was broken, the timber frame superstructure was exposed to loads which exceeded the design loads many times.

In most of the houses the "roof triangle" was not damaged. Also the "non load carrying walls" acted as load carrying to a great extent. As a matter of fact, the bathroom on the second floor seemed to be the most secure room in the whole building. Figures 16 and 17 show the frame system, the roof triangle and a sketch of possible damage development. In Figures 18 and 19 some details are shown.

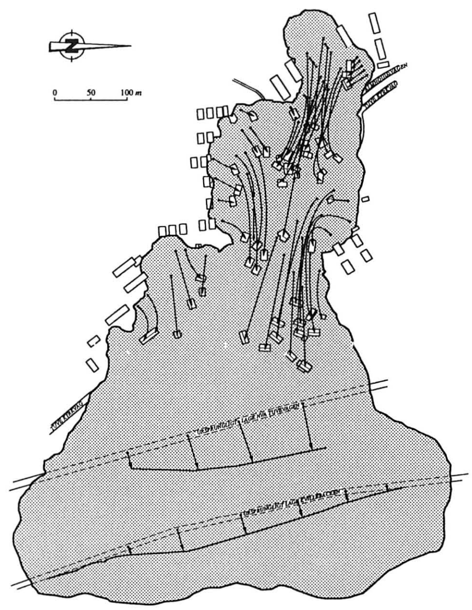
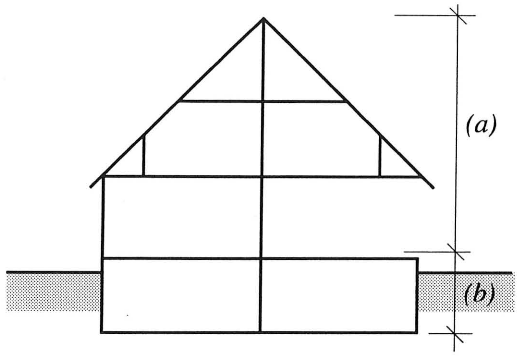
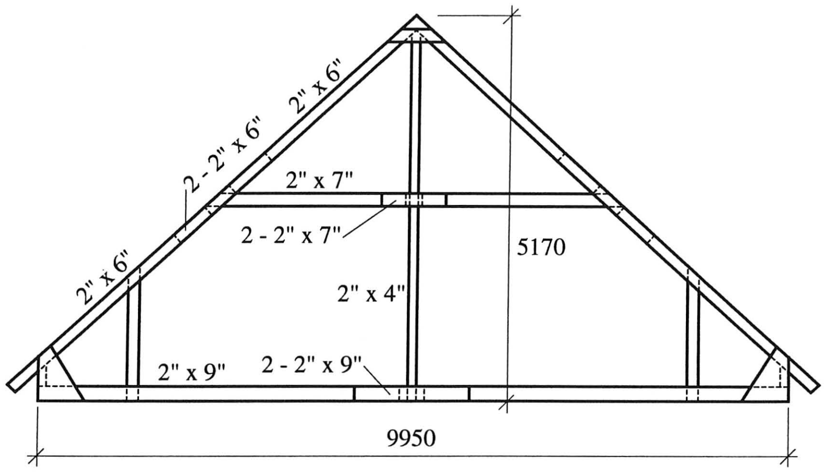


Figure 15 Map of the slide area with the direction the houses slid indicated.





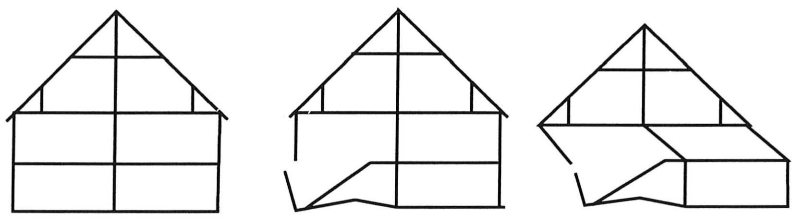


Figure 16/17 The frame system (top), the roof triangle (middle) and possible damage development (bottom). (a) timber, (b) concrete.

Figure 18/19/20 *Details of damaged houses at Almhöjdsvägen.*

Small-element houses

These houses were made of small wooden elements. Each element was built as a wooden box, about 200 *mm* square, length 2,5 *m*, filled with sawdust. The roof structure was a timber frame. The floor structure was light weight concrete elements. The connection between the wood elements and the floor structure was too weak. These houses lost their walls to a great extent. When most of the gable wall had fallen, the roof structure also broke. In one case a roof structure held together for four weeks before breaking. Probably the influence of humidity weakened the nailed joints.

There was one house in the slide area of the same type, except for the floor structure. This house had a timber floor structure, which made the whole house function as a closed square box. The concrete cellar was destroyed but the wooden superstructure was nearly intact, just a little deformed.

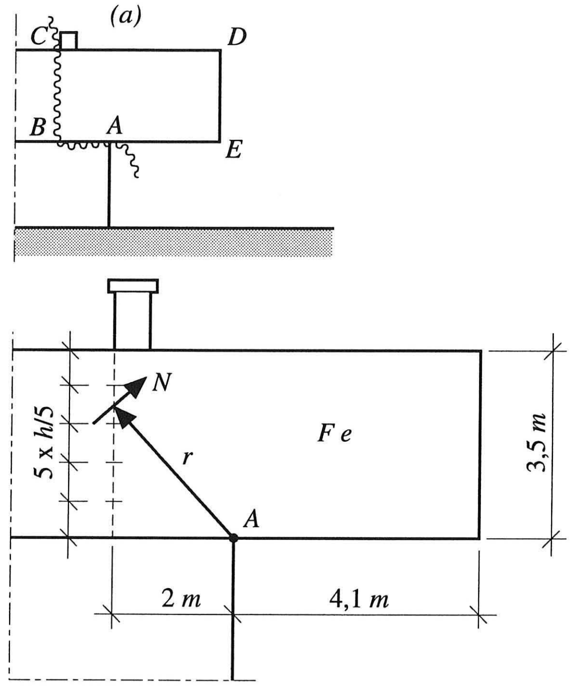


Figure 21 *Roof cantilever. (a) fracture.*

Figure 22/23 Photo of a house with roof cantilever. It is the same house on both pictures, the photo with the broken roof was taken four weeks later.

Ordinary element house

The house had a timber super structure built on concrete block walls in the basement. There were timber beams in the floor structure and timber trusses in the roof.

This house was very interesting. Although it had lost approximately 75% of its supporting basement walls, it did not break down, although it showed some deformation and a few broken windows. This is an excellent example of "box-function". A box with 4 stiffened walls (the inner walls act as stiffeners) and an intact top and bottom is rather stiff and safe. This was proved many times in the slide area. Figure 25/26 shows the building, resting on "nearly nothing".

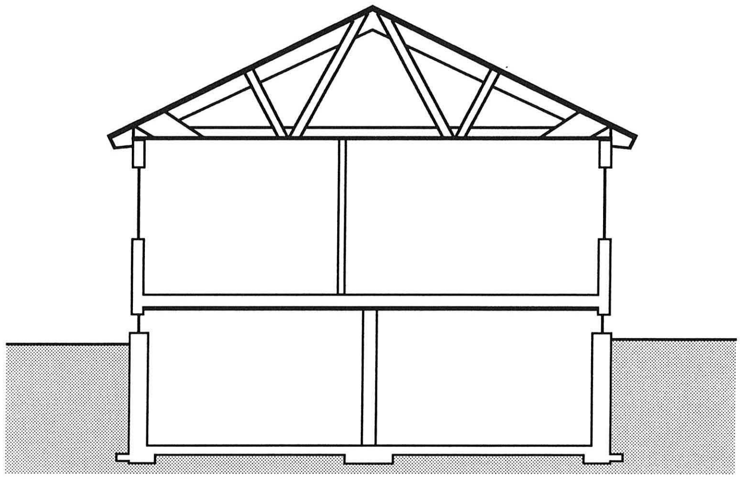


Figure 24 Section of the house.

Figure 25/26 The house rests only on the centre walls and cantilevers in all four directions. Notice the shear deformation in the window openings.

Summary

The reason for the storm damage in most cases can be traced to detailing performed as a matter of routine, overestimation of the strength of the connections, unsuitable design and structural details and negligence on the site. All parties involved in the construction process bear a share of the blame, no one is without blame.

Heavy snowloads sometimes combined with wind loads caused a lot of damage. The damage occurred mainly in light-weight structures like timber and steel structures. These are often more sensitive to excessive imposed loads. The most obvious conclusion from this investigation is that accurate design with appropriate loads gives a satisfactory level of safety against failures. Bad design and/or poor workmanship during construction or erection often result in structures where the failure load can easily be lower than the design load.

The behaviour of the houses in the landslide at Tuve very clearly showed that a "stiff" wood frame house can withstand a very severe load condition and yet hold together. The most impressive sight, however, was to see how the "roof triangle" in almost all houses kept "together" even if all walls had disappeared and the house had slid more than 100 metres.

The overall conclusion is that correct design procedures using accurate design loads result in buildings that can withstand severe load conditions very well. However, this naturally raises the question as to what a design load in different situations should be and what the proper design should be.

References

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