What is a robust construction?

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Introduction

Failures can in general be caused by flaws in the design or construction leading to a low load bearing capacity, or by an unforeseen incident giving rise to higher loads than expected.

The strategy for ensuring robustness might be different depending on which of the two causes that is thought of. This is illustrated below by the Siemens Arena case.

Siemens Arena

On one morning two trusses in the roof of Siemens Arena suddenly collapsed, see Figure 1. It happened just a few months after the inauguration of the arena and a few days before a major bicycle event should have taken place.

Each truss was composed by two glulam timber arches with vertical connectors, see Figure 1. The upper arch was mainly exposed to compression and the lower to tension. The horizontal component of the tension and compression forces were neutralised at the corner connections by concealed steel plates connected to both arches by embedded dowels and a few bolts, see Figure 2. The structure appeared as an elegant slim construction with a free span of 73 metres across the arena. The failure occurred suddenly at a time with almost no wind and only a few millimetres of snow.

An investigation [1] showed that the problem could be localised to one critical cross-section at the corner in the tension arch where the strength was between 25 and 30% of the required strength, see Figure 3. By mistake, this cross-section was not considered at all in the design.

Three errors explain what happened:

– A 48% too high design strength was used for the timber part
– The reduction of the height of the cross section near the ends of the arches, see Figure 2, was not considered
– The holes in the timber for steel plates, bolts and dowels, see Figure 3, were not considered

The expected short term strength at the critical cross section happened to be slightly larger than the forces from the self weight of the structure, whereas the long term strength was smaller. Therefore the collapse could take place at a time with no special external load.

The investigation also revealed that the stability of the trusses was not ensured sufficiently and that the quality of the glueing of the glulam was not as specified. These problems did not contribute to the actual failure.

The collapse did not reveal any unknown phenomenon, so the main question is how such a vital error could pass the quality assessment of the design.

Figure 1. The roof of Siemens Arena after the collapse of two trusses. An intact truss is seen to the right.

Figure 2. The corner where concealed steel plates connects the timber parts. Between the visible bolts numerous dowels are placed.

Figure 3. Rupture at the critical cross section in the corner connection. Note the dowels and steel plates.

Robustness strategies

The 12 m long purlins between the trusses were only moderately fastened, such that a failure of one truss should not initiate progressive collapse. This strategy proved to work fairly well as only two of the 12 trusses collapsed. As all trusses had much lower strength than required it might be fair to conclude that the extent of the collapse was *not* disproportionate to the cause.

Another and more expensive strategy against progressive collapse could have been to design the trusses, the purlins and their fastening such that a failed truss and the roof could hang in the purlins and transfer the load to the neighbour trusses (when considered an accidental load case).

Had the cause of the failure been a huge load on one truss this strategy would have been preferable because it significantly reduces the risk of injuries. The strategy would also have worked if a leaking roof had degraded one truss because it is likely that the other trusses are unharmed.

But given the cause of the actual collapse this strategy would most likely have caused a total failure as the neighbour trusses could not have withstood the extra load.

The bracing in the longitudinal direction was ensured by two systems, one at each gable. This ensures stability of the remnant part of the building when one truss has failed, no matter which truss. This strategy also proved successful, even though there was no wind or snow to call for big demands to the bracing system. If insufficient stability of the trusses had caused a failure the division of the bracing into two systems might also help, especially if both systems can sustain the entire load. With only one system there will most likely be key-elements for which failure will cause a total collapse.

Discussion

There is a significant difference between human errors and other incidents causing failures.

Human errors lead to a too low load bearing capacity and are therefore likely to cause failure for foreseeable loads. The ability of the structure to redistribute the load even in a parallel system might small because the other components are likely to inherent the same error and therefore also are weak. An attempt to enable redistribution might therefore cause a local failure to initiate a total collapse.

An unforeseen incident at a correctly designed and constructed construction might give rise to too high stresses, but most likely only in a small part of the structure. If the construction is a parallel system it is highly likely that the loads can be redistributed and sustained by the rest of the structure. If a series system is used this is of course not possible.

In principle robustness is aimed at reducing the risk of human injuries in the case of an unforeseen incident. It is assumed that the structure fulfils the requirements of the codes. Under these assumptions parallel systems are very attractive as they will minimise the consequences. Series systems can be overdesigned, but it is against the idea of robustness to try to design for an unforeseen incident.

But in real life most failures are related to human errors such that the structure does not fulfil the requirements. Limiting the consequences of a failure in case of a systematic human error demands that load is not significantly redistributed. Weak spots appear to be the only way to ensure that.

Therefore, when advising strategies for ensuring robustness it must be considered if the strategy might increase the consequences of human errors.