CROSS Safety Report

Collapse of unusual hybrid concrete-and-steel strand truss on school roof

This month we present a report about the collapse of a school hall roof, which resulted from the failure of one of a number of unusual hybrid concrete-and-steel strand trusses.

Report

This report concerns the partial collapse of a roof to a primary school hall. The collapse resulted from the failure of one of a number of unusual hybrid trusses. The trusses consisted of a precast reinforced concrete top chord and verticals with a bottom chord of tensioned steel strands. The failure of the truss **(Figure 1)** led to the collapse of the supported flat roof local to the truss, and a partial collapse of the adjacent roof. Fortunately, the collapse happened outside of school hours and when the hall was not in use.

These unusual hybrid trusses spanned the 10m wide hall, bearing on pockets in a precast ring beam which capped the external wall of the single storey building. The trusses were set at approximately 3.5m centres along the length of the building. The trusses supported precast concrete purlins over which were woodwool slabs, insulation and a felt roofing finish.

The bottom chord of the truss **(Figure 2)** consisted of seven steel strands. The strands extended for the full length of the truss between anchorage plates cast into either end of the reinforced concrete top chord. The strands passed over four steel mounts located at the ends of concrete verticals cast integral with the top chord. Stability of the top chord was provided through diaphragm action of the woodwool slabs, thin screed and purlins, distributing lateral loads to masonry cross walls. It is thought that the building may have been constructed in the 1950s.

The reporter, a structural engineer, visited the site soon after the collapse. The roof truss had failed with six of the seven steel tensioning strands lying on the ground. The anchorage fixings for the detached end of the loose strands were found in the bearing pocket of the edge beam. The anchorages for the other end of the strands remained with the top chord endplate. The purlins on either side had collapsed or were damaged and hanging from one end, but the felt roof was still intact and holding water.

The reporter considered that, at the time of construction, the purlins would only have had a bearing of around 20mm and there was evidence that they had been bedded on mortar in pockets on top of the truss. It appears that, probably around the time of construction, a steel angle was fixed to the top chord of the trusses to provide additional support to the purlins, presumably owing to their small bearing width.

The tensioned strands were held at the endplates using a cylinder with two serrated split wedges **(Figure 3)**. The strands were carried over the concrete verticals on support rollers. It was not clear to the reporter how the truss was originally tensioned. The reporter says that there may have been an initial tensioning at the factory, with further tensioning prior to installation using the threads on the steel mounts to lengthen the verticals, thus tensioning the strands. **Figure 4** shows the steel mounts and strand support rollers.

The reporter goes on to say that concrete from the failed truss was tested in a laboratory and found not to have any significant defects. Some surface corrosion of the reinforcement was observed, but this could be expected from a concrete element of this age. The detailing of the reinforcement, however, did

↑FIGURE 1: Failed truss and partially collapsed roof

FIGURE 2: Elevation and section through truss

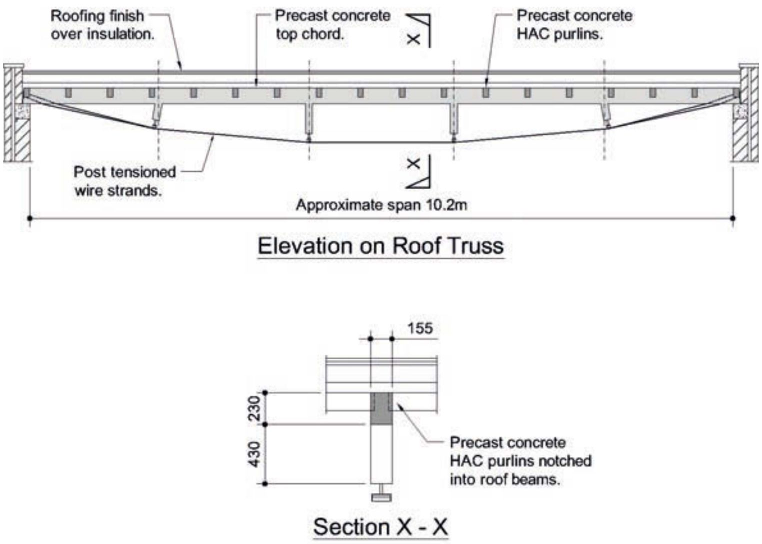

FIGURE 3: Anchoring cylinder with two split wedges

not appear optimal; the bars were lapped in the middle of the top chord with a non-standard detail. Furthermore, the reinforcement did not fully extend to the beam end and the bearing appeared to be minimally reinforced. There was also minimal link reinforcement at the end of the beam where the anchorages failed, although there was no shear cracking at the end of the failed truss. There was some surface corrosion to anchor plates and the tensioning strands, but no loss of section was visible. Testing confirmed that the concrete in the purlins was made using high alumina cement. Degradation was apparent in some of the purlins which suggests that conversion had taken place and reduced the structural integrity of the purlins. The reporter's inspection did not identify any significant cracking or distress to the hall structure below the eaves level concrete ring beam.

The reporter believed the failure possibly resulted from anchorages of the tensioning strands slipping suddenly without warning. This could have led to a global failure of the truss in bending, as witnessed by the significant deflection and damage that occurred at the centre of the span. The reporter reasoned that once the anchorages had slipped, tension was lost in the strands and, owing to the poor detailing of the reinforcement at mid span, combined with the reduced capacity of the concrete chord, the truss likely failed in bending at mid span and collapsed. This caused the purlins to become dislodged and the roof structure in the two bays on either side of the truss to fail and deflect or collapse to the ground.

The reporter goes on to say the inherently defective nature of the truss system, exacerbated by creep and age, combined with poor reinforcement detailing and the poor detailing of bearing notches for concrete roof purlins may have all contributed to the failure. The reporter adds that the roofing felt was proven to be watertight by the fact that it held water that accumulated in the deflected roof structure until the felt was pierced during subsequent demolition. The roof felt held a considerable amount of water, but there was no evidence of an accumulation of water at roof level prior to the collapse, and there was no evidence that the roof drainage was defective in any way.

The reporter wishes the details of the failure to be disseminated so that trusses of this type in schools or other buildings can be identified and appropriate measures be taken.

Expert Panel comments

This could have been a very serious incident had the school hall been occupied at the time of the collapse. The construction method is unusual and it is important to share findings to help prevent other similar events.

Unusual structural systems do exist

Variations of the reported concrete structure have been used in bridges, and a similar structural system has also been used in timber trusses. A concrete truss system where precast units were transported to site and then stressed together is also known to have been manufactured. This collapse serves to emphasise that bodies responsible for the safety of buildings must be aware that novel structural systems, as illustrated in this case, may pose safety risks.

Potential causes of failure

The reporter did not know the cause of the failure although they believe it was possibly associated with the strand anchorages. A number of causes could be postulated, and it is likely that a combination of causes led to the collapse. A failure of a tendon or tendon anchorage is one potential cause. Movements at the truss end bearing could be a contributory cause, promoting crack development around the anchorage and loss of anchorage or disruption of the top chord. Creep stretching of the tendons causing sagging of the truss and the potential for rainwater ponding could be an exacerbating factor. Replacement roof coverings could have also had an impact over time.

It should also be borne in mind that a truss of this type would have very low horizontal stiffness and the lateral stability of the top chord could therefore be susceptible to being compromised. The lightweight nature of the roof deck and very small purlin bearings may mean the construction is not particularly robust, and lateral restraint to the trusses could be lost which would have been very

FIGURE 4: Steel mount on concrete vertical carrying tensioned strands

detrimental. Although not reported in this case, where woodwool slabs are subject to water damage, their ability to accept and distribute loadings could be reduced.

Suffice to say, a number of different effects, including, creep, thermal movements, load changes and damage, could have been at play and led to a sudden or progressive failure of the truss bearing, tendons or tendon anchorages. It is known that the truss was in the order of 60 to 70 years old at failure and, therefore, beyond reasonable expectations of its service life.

SCOSS (now CROSS) published its alert *Tension cable and rod connectors* in 2012, which concerned the failure of tension cable and rod systems.

Critical details should not be hidden

It is not good practice to have critical details, such as anchorages, in a location where they are not easily inspectable, as appears to be the case with this failure. Any structure which relies on strands or cables for its structural integrity should be designed such that the terminations are visible and easily inspected. The inspection of strand and cable terminations needs an experienced eye as potential issues are often not immediately apparent. Persons inspecting buildings should be mindful that critical parts of a structure may be hidden from view.

Keep robustness in mind

It may be the case that the trusses themselves, and the adjacent decking providing restraint, are not particularly robust. The robustness of the structural system and the nature of any particular modes of failure, particularly those without warning, should be considered during the design or inspection of structures. While not thought to be a contributing factor in this case, the presence of high alumina cement (HAC) concrete should be noted. Its rapid strength development made HAC popular from 1950 to 1970, but, mineralogical 'conversion' sometimes caused reductions in concrete strength and increased vulnerability to chemical attacks.

Inspection regimes based on risk

Those bodies and persons responsible for the safety of buildings, should understand that these deteriorate over time, and in doing so, the risk of failure increases. Structural elements constructed in the 1950s and 60s may now have reached the stage of being beyond a reasonable expectation of their design life. Inspection methodologies for buildings should take into account matters that influence risk such as age, exposure conditions, usage, construction type and previous inspection and maintenance strategy. Likely failure types and consequences should also be considered; the failure reported here could be considered a sudden failure, the type of failure to be guarded against, as there was no apparent warning. Inspection regimes should recognise such issues, and focus resources using a risk-based approach. Inspection and assessment of buildings should be done on a regular basis.

CROSS recommends that responsible bodies or persons arrange for appropriate inspection and assessment of buildings that contain unusual forms of construction, including roofs similar to the reported failure, and take appropriate action following the assessment. Structural inspections and assessments should be undertaken by engineers who are suitably qualified and experienced persons. Key points to look out for include the following (there may be others in specific cases):

- structural forms that are unusual in terms of innovative design or materials
- buildings that would pose high safety risks to the occupants if they collapsed
- buildings that are manifestly old and were designed to outdated codes
- structures with minimal redundancy
- obvious signs of deflection, leaning, leakage, cracking, corrosion, or damage
- fixings or bearings that are hidden and may require intrusive investigation.

The discovery of such features does not mean there is a high risk but it may mean that a detailed investigation is needed.

SCOSS published the topic paper *Assessment and inspection of buildings, and other facilities* in 2003. While some aspects of this paper arguably require updating, it may still be a useful reference to those persons involved in considering inspection methodologies.

The Institution of Structural Engineers' publication, *Guide to surveys and inspections of buildings and associated structures*, contains general guidance on the subject as does its publication, *Appraisal of existing structures* (Third edition).

The full report, including links to guidance mentioned, is available on the CROSS website (report ID: 1227) at **www.cross-safety.org/uk/safety-information/cross-safety-report/collapse-unusual-hybrid-concrete-and-steel-strand-1227**

Key learning outcomes

For owners and persons responsible for the safety of buildings including schools:

- Inspect and assess existing buildings, particularly those that might have been constructed over 50 years ago, to see if they contain unusual forms of construction, including roofs similar to the reported failure
- If so, or if there is doubt, arrange for structural inspections and risk assessments to be undertaken by engineers who are suitably qualified and experienced persons (SQEP) – normally chartered structural engineers

For inspecting engineers:

- Undertake a risk assessment of old and unusual structures where there is a life-safety risk should they fail
- Consider what combination of causes could lead to a structural failure
- Understand where structural elements may be beyond their reasonable service life
- Look out for signs of distress while noting that some of these may be in hidden components or locations