Fixing Failures – Case Study 1

Collapse of a concrete ceiling on Intestate 90 Connection Tunnel in Boston – July 2006

**An article for the
Construction Fixings Association**

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*This is the first case study in the "Fixing Failures" series intended to illustrate some of the factors which can contribute to fatal outcomes if Best Fixings Practice is not followed. Nothing stated here is intended to imply a conclusion on the part of the CFA or the author as to the actual cause of the failure as there are various factors involved. However – failures did happen so we must consider the possible causes in order to avoid them in future.**

Background

On 10 July 2006 sections of concrete ceiling panels fell from the roof of a road tunnel in Boston (a section of the so called Big Dig) killing the lady passenger of a car travelling beneath. The panels had been suspended from the concrete roof, to form ventilation ducts, using hangers, each fixed with anchor rods set in epoxy resin. The original installations were made between 1999 and 2000.

The failure of the anchors was investigated by the National Transportation Safety Board (NTSB) who issued a report on the anniversary of the accident.

The report makes a large number of recommendations for a wide range of bodies involved including the manufacturers, specifiers and suppliers of the fixings.

As a responsible body representing the major suppliers of construction fixings within the UK, including resin anchoring systems, the Construction Fixings Association sees the need to set out the salient facts as far as they are currently known in order to reassure specifiers regarding the use of resin systems sourced within the UK and to ensure that they are aware of some of the management failures which may have contributed to the accident so that a similar tragedy can be avoided.

NTSB conclusions

Among many conclusions reached the major finding is that " the probable cause ….. was the use of an epoxy anchor adhesive with poor creep resistance, …..".

The report also points to "… a lack of understanding and knowledge in the construction community about creep in adhesive anchoring systems."

There had been displacement of a number of anchors prior to the accident and the report goes into a great deal of detail regarding these problems including a) the installation process b) the testing regime used to validate that anchors had been correctly installed and c) the investigation into the displaced anchors that was carried out at the time. It is critical of all three.

Despite this the main conclusion of the report is that it was the use of an inappropriate resin material that was the major cause. While this is a serious aspect it should not form the sole focus of engineers' concerns.

The specification

One question that has been asked is – "Why was a resin system chosen when other systems might have been equally suitable and easier to install overhead". In fact undercut anchors had been considered but discounted due to problems on an earlier part of the project. Unfortunately the report goes no further into this aspect so no details of the nature of those problems is readily available. From the perspective of 2008 and knowing how reliable and easy to install undercut anchors now are it is hard to understand why that approach, or an alternative mechanical anchor, was not pursued. We must also remember that at the time when this project was being specified, around 1997, European Technical Approvals were only just being awarded – to Throughbolt type expansion anchors - and it would be some time before Undercuts and Resin Systems were available with ETAs although such anchor types were available with national approvals.
It is also true to say that while installing resin anchors overhead is not easy it is possible and installing capsule systems overhead is generally easier than injection systems.

The Resin System Used

The NTSB investigation was thorough in identifying the actual resin found in the failed anchorages by a series of chemical analysis tests and comes to the unequivocal conclusion that the resin used was an epoxy resin made available in two versions a standard setting version and a faster setting version (curing times in relation to other anchor types are explained below). It was the faster setting version that the report concludes was used in the anchors in the area of the failures.

The report concludes that it was the poor creep performance of this resin that lead to anchors eventually failing after 6 years in service.

The NTSB report implies that the faster setting version of the resin had, at the time the design was being considered (1997–9) been subjected to a creep test carried out against the requirements of ICBO - AC58[i] and had failed. The standard setting version had passed. However the NTSB also had tests carried out during the investigation and found that the faster setting version of the resin suffered unacceptable displacements at relatively low loads (loads lower than the design load of the ceiling hangers) while the standard setting version suffered minimal displacements at all test loads including loads above the design load of the hangers.
The manufacturers of the system have issued a statement to the effect that:
a) they had informed officials about the creep characteristics of fast setting epoxies, including their own product,
b) the faster setting version of the epoxy had failed to pass a creep test by a 'significant margin',
c) it was approved by the ICBO only for short term loading, and
d) creep was a problem with all fast setting epoxies.
It is understood that the manufacturer has also claimed that they were under the impression that it was the standard setting version, that had actually been installed in the job.

Creep

This is a phenomenon whereby an anchor may be capable of supporting a certain load during a short term test but may exhibit significant displacements and eventually fail when subjected to the same loads over a sustained period.
It is well known within the fixings industry that certain types of resin are more prone to creep than others, this depends on the precise formulation and formulations vary significantly even between resins of basically similar types. It is not usual to offer resins with poor creep characteristics for use as anchoring products at all because all applications where a fixture is clamped down by tightening a nut or bolt will be subject to a sustained load for their design life. In order to determine the long term creep characteristics of a particular resin material the anchor is subjected to a sustained load test carried out over a period of several months and the measured displacements are analysed in such a way as to predict the long term performance.

Creep as such is rarely referred to by fixing manufacturers as its effect, along with other factors affecting the anchor performance, is taken into account in determining safe working loads.

In Europe anchors may be awarded a European Technical Approval (ETA) against the requirements of an ETAG[ii]. For bonded anchors the possibility of creep is ruled out by a sustained load test carried out over a period of at least three months and analysed in such a way as to predict long term performance for up to 50 years. There are requirements on the displacements which must be satisfied for the anchor to gain an approval with the quoted loads. Similarly if a bonded anchor is intended to be used overhead the test regime must demonstrate that this can be achieved satisfactorily with the manufacturer's recommended installation method.

What about resin systems sold in the UK?

First it is useful to clarify the different types of resin available on the UK market.

They can be crudely divided into two groups. One group contains those which use catalytic curing, where mixing of the resin and a catalyst prompts the curing, or hardening, of the resin.
The other group contains those which do not use catalytic curing and where mixing of two components leads to a chemical reaction which again develops into a very hard resin.

The majority of applications in the UK are satisfied by resins in the first group. These are known by names such as Vinylester, Polyester, Methacrylate and Hybrid. These types, while different in formulation, all cure by the action of catalysts and have relatively fast curing times.
Epoxy resins on the other hand fall into the second group as they are not cured by a catalyst but by the chemical reaction between two components. As a result curing times are much slower. For this reason they tend to be specified only when their special characteristics of high strength and low shrinkage are particularly useful.

It is worth noting that the epoxy resin allegedly used in the Boston Tunnel would still cure very much more slowly than any of the catalytically cured resins.

What are the relative curing times of these anchors?

Typically an injection type of vinylester or hybrid resin will cure in about 60 minutes at temperatures between +10 and +20°C; (the same resin used in capsule format will take only about 20 minutes) whereas a "normal" epoxy (only available in injection format) may take 12 – 16 hours at these temperatures.

What types of resin do CFA members supply?

None of the members of the CFA* supplies either version of the resin used in the Boston accident.

All members of the CFA supply a range of different resins, some including epoxies, but none supplies an epoxy resin of the same formulation as that which failed in Boston.

Most members of the CFA have within their range at least one resin anchor with a European Technical Approval and those that don't are acquiring ETAs.

The installation

Of the twenty anchors found to have failed in the area of the accident nineteen were found to have voids in the area of the resin bond of between 3 and 38%. A void of 38% could, in the opinion of the undersigned, contribute significantly to the risk of failure especially if the other sixty two percent of the bonded area had not been properly cleaned. (The effectiveness of cleaning and the existence of residual dust from the drilling process are, in the experience of the author, difficult to identify from failed anchors due to the damage to the cured resin as it is dragged from the concrete but the NTSB report does claim that dust was present in the holes and suggests that hole cleaning had been inadequate.) However despite this the NTSB does not place significant emphasis on this aspect, serious as it might have been, as the loss of performance in their creep tests suggests that the anchors would have failed at some stage even if they had been satisfactorily installed with no voids.

Current installation methods

All resin anchors require thorough hole cleaning, usually by means of a suitable brush (to loosen drilling dust adhering to the hole sides) along with a blow out pump, vacuum cleaner or air line (as long as it passes no oil) with a nozzle reaching to the base of the hole. Systems for installing injection resin overhead are available which include techniques to ensure voids are not introduced and that the resin is retained in the hole.

Early signs of problems

Early signs of problems were evident from two sources.

i) A series of proof tests was carried out as a condition of the contract. Tensile tests were required to be carried out on all anchors to a load of 125% of the design load. There were regular failures during this programme. One report recorded 548 tests with 38 failures – almost 7%. Failed anchors were removed and replaced. The level of failures did not appear to have been regarded as sufficiently serious as to warrant a full investigation of just why such a high proportion of anchors were failing at such a relatively low proportion of their full potential.

ii) Several anchors installed in a test area were noticed to have slipped by up to half an inch over a period of only two months.
The anchor found to have the highest displacement (9/16 inch) was subject to a tensile test to 3250 lbf (125% of the design load) some three and a half months after it had satisfactorily held the same load. This time however it sustained the load for only a few seconds then pulled out with "almost no resistance". Various inadequacies in the installation were found including insufficient resin, poor resin mixing and residual concrete dust indicating poor hole cleaning. The slipping anchors were investigated quite thoroughly but the possibility of failure due to creep was never considered nor was a satisfactory conclusion regarding the cause of the problem agreed by all parties.

CFA position

None of the comments made in this discussion document are intended to be an endorsement of the conclusions of the NTSB report. While legal action is still pending the true facts may take some time to come to light.

If a resin with poor creep characteristics were used and if the tests carried out by the NTSB are typical of the characteristics of the resin that was used then it would appear that failure was indeed likely at some stage. This does not mean that the evidence of poor installation should be ignored. The report's findings that a significant proportion of the anchors in the area of the failure had significant voids along with evidence of dust in the hole and poor mixing, if proven to be well founded, suggest that the overall safety margin was dramatically reduced and when combined with the poor creep characteristics a catastrophic failure was inevitable. These factors do explain the high level of failures under proof testing and the displacements of working anchors.

The continual evidence of poor installations provided by the failure of proof load tests together with the displacements found in a significant proportion of working anchors should have caused a complete rethink of the specification.

Specifiers of anchoring systems in the UK can take comfort from the fact that none of the major manufacturers supplies the type of epoxy used in this project resin nor a similar formulation. But they should heed the warning that such installations must be correctly installed and put in place measures to ensure they are. Such measures are outlined in the introductory article to this series.

Advice relating to completed projects.

In relation to projects already completed interested parties are recommended to contact the manufacturer of the resin used who, if they are a member of the CFA, will be able to confirm the characteristics of their resin systems and their suitability for the application concerned.
Where doubts about installation quality arise a proof testing regime may be worth instigating, as described below.

Advice relating to new projects.

Many resin anchors are now available with European Technical Approvals (ETA). As part of the exhaustive testing programme all approved resin anchors will have satisfied the requirements of a sustained load test which will endorse the application of the relevant loads quoted in the ETA for a design life of 50 years. The direction of installation will also have been taken into account in the testing regime so an anchor approved for installation overhead can be relied upon to function correctly - as long as the manufacturer's recommended installation instructions are followed, as they should be for any anchoring system. Some national approvals also cover long term loading in a similar manner. For anchors without approvals talk to the manufacturer about long term loading capabilities.

Most CFA members have at least one resin anchor in their range with an ETA or are in the process of acquiring them.

All the members of the CFA have made their staff aware of the issue of long term creep of resin systems so that they know how to handle enquires with long term sustained load requirements.

Proof test regimes.

It must be borne in mind that not all applications nor all anchor types require proof testing regimes. They may be called for when the application is particularly safety related but all anchors that have been awarded an ETA will be as fool proof to install as is reasonable and some even give an indication of correct setting which is evident to an inspecting engineer immediately after installation. Nevertheless the possibility for human error is ever present and despite thorough training and supervision there will always be cases where it is prudent to insist on proof tests.

The procedure for proof tests is outlined in the CFA Guidance Note: *Procedure for site testing construction fixings*.

Sampling rates should be chosen to reflect the nature of the safety relevance of the application, the likelihood of human error and the consequences of a failure.

Where these factors are high an initial sampling rate as high as 10% may be justified. Consistent satisfactory results can then be the justification for a reduction in the sampling rate while any failures at all must be treated seriously, the cause identified to enable future installations to be corrected and the sampling rate increased, possibly to 100% if necessary, until confidence is restored.

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* This article has been revised on 1 October 2008 in order to remove references to brand names as they are not pertinent to the discussion of potential causes of anchor failure.

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[i] ICBO International Conference of Building Officials. Acceptance Criteria 58.
[ii] ETAG 001 *European Technical Approval Guideline for Metal anchors used in concrete*. Published by EOTA at www.eota.be. Part 5 covers the requirements for Bonded Anchors.