A HISTORICAL REVIEW OF THE USE OF EPOXY PROTECTED STRAND FOR PRESTRESSED ROCK ANCHORS

DR. DONALD A. BRUCE[1]

ABSTRACT

Fusion bonded epoxy protected strand has been used in post tensioning applications in North America since 1983, with the first ground anchor project undertaken in 1985. The product has been used in dam anchor tendons since 1991. A recent and significant problem at Wirtz Dam, TX has focused industry attention on vital issues relating to the production, testing, specification, installation, and stressing of the material. It is clear that this problem has raised questions in the industry regarding the use of the product, but the author believes that through the development and application of appropriate codes, standards, recommendations, and specifications, the inherent advantages of the material can again be routinely exploited in sensible fashion for mutual benefit. The paper provides a historical and technical overview of the use of epoxy protected tendons, primarily in dam rehabilitation.

BACKGROUND

The process of applying fusion bonded epoxy coating to 0.6-inch diameter, 7-wire prestressing strand appears to have been developed commercially in 1981, following earlier experiences with epoxy coated reinforcing bar. According to Bonomo (1994), the product was first commercially used in 1983 to post tension a precast concrete floating dock in Portsmouth, VA. Until 1985, epoxy protected strand was used only in structural/building related projects. Early examples of its use include the Bayview cable stay bridge in Quincy, IL (1984) and post tensioned pier caps on I-495 in Rochester, NY (1988).

Although ground anchor practice in the United States has enjoyed a long, successful and internationally acclaimed reputation (Bruce, 1997) one area in which it differed from European concepts was in its somewhat more relaxed approach to corrosion protection. For example, what British practice (BS8081, 1989) regarded as single corrosion protection (i.e., the use of a protective corrugated sheath, grouted in situ) U.S. specialists typically referred to as double corrosion protection. The difference lay in the interpretation of the reliability of the grout in the bond zone as an acceptable layer of corrosion protection. Thus while the British tended not to count the grout as a reliable and permissible layer of corrosion protection since it could crack during stressing due to its strain differential with the far more elastic steel it encased, others disagreed. It was argued that any stress fractures would be of very small aperture, and that the highly

[1] President, Geosystems LP, P.O. Box 237, Venetia, Pa 15367, U.S.A.; Phone: 724 942-0570; E-mail: dabruce@geosystemsbruce.com

alkaline environment of the grout would prevent acid corrosion of the steel – should it actually be exposed to direct contact with continually aggressive groundwater in any case. No case has been reported, nevertheless, of failure resulting from bond length corrosion in a properly grouted anchor.

Around the same period in the late 1980s, U.S. contractors installing permanent ground anchors began to realize that the use of a corrugated plastic duct as corrosion protection over the bond length required special attention to construction detail during the grouting operation (e.g., tremie tubes inside and outside the sheath, grouted in careful sequence to avoid structural distress to the sheath due to differential fluid grout pressures); as well as demanding larger diameter drill holes to accommodate the tendon, the corrugated sheath, and the multiple tremie tubes with appropriate thicknesses of grout cover.

It was logical, therefore, that epoxy protected strand should become considered for strand tendons: it removed the necessity for a separate tendon protective encapsulating sheath, allowed hole diameters to be minimized, and simplified the grouting operation. Such construction efficiencies would have the potential to offset the far higher material costs of such strand. Its first use in an anchoring application was to stabilize the foundation of a private residence in Malibu, CA, in 1985, while the first *major* anchoring project was a permanent tieback wall at the Los Angeles City Library in 1989. This followed a smaller similar project in Phoenix, AZ, in 1988. However, little interest seems to have been generated within the ground anchor community during this period, and high capacity permanent anchors for high dams continued to be installed using only grout as the definitive (and sole) barrier to corrosion of the tendon in the bond length (e.g., Bruce, 1989).

In contrast, the Bureau of Reclamation specified in 1990 (following 3 years of market research) the use of epoxy coated strand for the seismic rehabilitation of Stewart Mountain Dam, AZ, incorporating long, high capacity tendons (Bruce et al., 1992). Here, the Bureau were concerned about the impact that such high, concentrated, compressive prestress loads could have on their tall, thin arch dam. They therefore mandated that the tendons should be installed, primary grouted, stressed, and then monitored (together with the structure) over a period of 90 days to assure acceptable performance of both anchors and structure. Given successful performance of dam (and anchors) under this new loading condition, the tendons would then have their free lengths grouted in a secondary operation. However, the structural engineers required, for seismic considerations, that the tendons be fully bonded by grout to the dam in the free length also: this meant that the tendon in the free length could not be protected conventionally over the 90-day observation period (i.e., by extruded or greased and sheathed, plastic coating) during which time there was considerable concern about the corrosive effect of the ambient conditions on the exposed, unsheathed tendon free length. The Bureau therefore specified epoxy coated strand ("Flo-Bond", from Florida Wire and Cable) as the tendon material. The project was conducted expeditiously, and the case history was widely promoted by dam owner, anchor contractor, tendon supplier, and strand manufacturer alike. Industry was keen to emulate and take advantage of this success and many projects followed. By the end of 1991, "Flo-Bond" was replaced as the material of tendon choice by "Flo-Bond-Flo-Fill", a product wherein epoxy was also introduced around the central wire of each strand, to guard against the possibility of water "wicking" up the otherwise unfilled interstices surrounding the central wire.

In 1992, ASTM A882/A882M-92 "Standard Specification for Epoxy Coated Seven Wire Prestressing Steel Strand" was published, followed by a PCI publication, "Guidelines for the Use of Epoxy Coated Strand." In a significant paper that did not receive commensurate attention, Bonomo (1994) further promoted the use of the material while strongly advised against stripping the epoxy coating off the strand in the stressing tails, a practice which was becoming common, especially on the earlier projects, mainly east of the Mississippi. He provided specific guidance on certain "unique properties" of the epoxy protected material:

- Relaxation: Losses are higher than for bare strand. In a 1000-hour test at 70% Guaranteed Ultimate Tensile Strength (GUTS), the loss in bare strand (low relaxation) was 1.5% compared to 4% in "Flo-bond" and 5.2% in "Flo-bond-Flo-fill."
- Creep: For a short period of time during the load hold test, both types of epoxy strand "undergo creep at a rate appreciably greater than that experienced by uncoated strand." He did conclude, however, that the long term performance of the material "is not impaired by the initial creep, which can be allowed for in the design of the anchor."
- Wedge Seating Loss: At ¾-inch, is significantly higher than that of bare strand (⅜ inch) at 80% GUTS. The initial creep that occurs during the load hold test will reduce subsequent relaxation losses. Emphasis was placed on the merits of correct wedge design to assure proper seating performance at Lock Off.
- Construction Issues: Special care during handling, and installation was recommended, together with (routine) cleanliness of the anchorage hardware, and correct tendon/jack alignment (especially for inclined anchors).

During the period 1993 to 1995, the Rock and Soil Anchor Committee of the Post Tensioning Institute (PTI), under the chairmanship of Heinz Nierlich, drafted completely revised Recommendations later published in 1996. These Recommendations included a new and enhanced approach to corrosion protection (Nierlich and Bruce, 1997). In particular, the terms "Double" and "Single" Corrosion Protection were dispensed with, in favor of the less judgmental terms "Class I and II" levels of corrosion protection, as summarized in Table 1. The acceptability of epoxy protected strand was thereby endorsed by the PTI Committee with respect to its corrosion protection capability.

The PTI guidelines for estimating creep in epoxy protected strand during the load hold test were in fact based on tests conducted by Florida Wire and Cable in 1993. The Recommendations consequently state, "The creep behavior of epoxy filled strand itself is significant and the measured anchor creep movements must be adjusted to reflect the behavior of the material. At a Test Load of 80% F_{pu} (GUTS), creep movements of epoxy filled strand are conservatively estimated to be 0.015% of the apparent free stressing length during the 6-60 minute log cycle, but may

Table 1. Corrosion Protection Requirements as Recommended by PTI, 1996.

Class	Protection Requirements		
	Anchorage	Unbonded Length	Tendon Bond Length
I Encapsulated Tendon	1. Trumpet 2. Cover, if exposed	1. Grease-filled sheath, or 2. Grout-filled sheath, or 3. Epoxy for fully bonded anchors	1. Grout-filled encapsulation, or 2. Epoxy
II Grout Protected Tendon	1. Trumpet 2. Cover, if exposed	1. Grease-filled sheath, or 2. Heat shrink sleeve	Grout

be higher than this value. For a Test Load of 75% of F_{pu}, this percentage can be reduced to 0.012%. These correction factors are based on limited laboratory tests, but appear to be reasonable based on field observations."

As described in the following sections, issues were encountered regarding the short term performance of a few anchors on certain projects in the early and mid 1990s. Construction deficiencies usually involving "first time user" contractors led to sudden slippage of strands through the wedges, resulting from tendon misalignment and/or dirty or grouted up top anchorage components. Creep losses beyond those allowed for in the then prevailing PTI Recommendations (i.e., the 1986 Edition) also created concern among owners otherwise acquainted only with the performance of bare strand tendons. Although general comfort was provided in the 1996 Recommendations, certain owners encouraged further research prior to permitting the use of epoxy protected strand.

For example, prior to the anchoring of Minidoka Dam, ID, in 1997, Florida Wire and Cable (still at the time the only manufacturer of the product in the United States) had indicated that changes in their manufacturing processes may have reduced the amount of creep in their product. The designers of the Minidoka project therefore required that further creep testing be conducted by the manufacturer on the new strand (Trojanowski et al., 1997). Based on tests on 16-foot lengths, at 80% GUTS, the creep was found to be 0.008% of the free length in the 6-60 minute log cycle. The following formulae were therefore specified for estimating the creep to be expected on the project:

- 1-10 minutes: 0.04% of free length
- 6-60 minutes: 0.01% of free length

Creep amounts so calculated would be subtracted from the total creep recorded in the field, and the net value compared to the limits recommended in PTI (1996) for bare strand.

Adding further fuel to the debate, Lang (2000) cited even more recent test data which indicate creep from 1-60 minutes to be 0.0214 to 0.0557% free length at loads varying from 70 to 80% GUTS.

The catalyst for this current initiative was the case of Wirtz Dam, TX in 1999. On this major project, several instances were found in early installed anchors of wedge slippage within 48 hours of Lock Off, together with observations of epoxy delamination from the strand. All tendons had previously performed well during routine Performance Testing. Closer examination of the tendons also revealed an unacceptably high frequency of windows in the corrosion protection ("holidays") (Frithiof and Krumm, 2000). Questions were raised regarding the uniformity of the thickness and adhesion of the epoxy coating, and so its ability to behave satisfactorily in the short term during stressing and Lock Off, and to satisfy the long term corrosion protection goals. These problems precipitated detailed forensic investigations by the various parties involved in the Wirtz Dam project and the findings elevated the issue to one of general discussion in the anchor industry (Aschenbroich, 2000).

This situation culminated in the formation in 2000 of an Epoxy Coated Strand Task Force, under the auspices of ADSC: The International Association of Foundation Drilling (Lang, 2000). The impetus for this came primarily from the post tensioning companies who assemble the tendons, provide the top anchorage hardware and jacks, and supply stressing expertise. One of the main goals set by the new chairman of this Task Force, Christopher Lang, was to write a supplement to the PTI Recommendations of 1996, dealing specifically and solely with issues relating to epoxy coated strand in ground anchors. This is scheduled to complete by mid 2002. A further goal of the ADSC Task Force has been to collect published and unpublished data regarding the historical size and value of the epoxy coated anchor tendon market over the years. At the same time, the ASTM A882 Committee has also been active in revising the standard to improve controls over the quality and consistency of the production processes.

This paper provides a brief summary of the major preliminary findings of the Task Force's efforts to date and is the first in a series of papers to be authored by members of the Task Force. It is hoped that this paper will stimulate critical debate and attract more data.

HISTORY AND USAGE

Based on a survey of suppliers, owners, consultants, and contractors, supplemented by published data and the proceedings of successive Task Force meetings, the author has generated the data shown in Table 2 and Figure 1. During the period from first usage in 1985 to early 2002 there would appear to have been 47 projects (some being consecutive, but separate contracts on the same structure), of which 33 were related to dam or hydro schemes. During the period from 1990 to 2001, it is estimated that between 100 and 120 dams and hydro facilities were repaired by prestressed rock anchors in North America, at a total price of $200 to 300 million. Therefore it would seem that, overall, around 30% of the projects involved epoxy protected strand with an estimated 25% of each project's

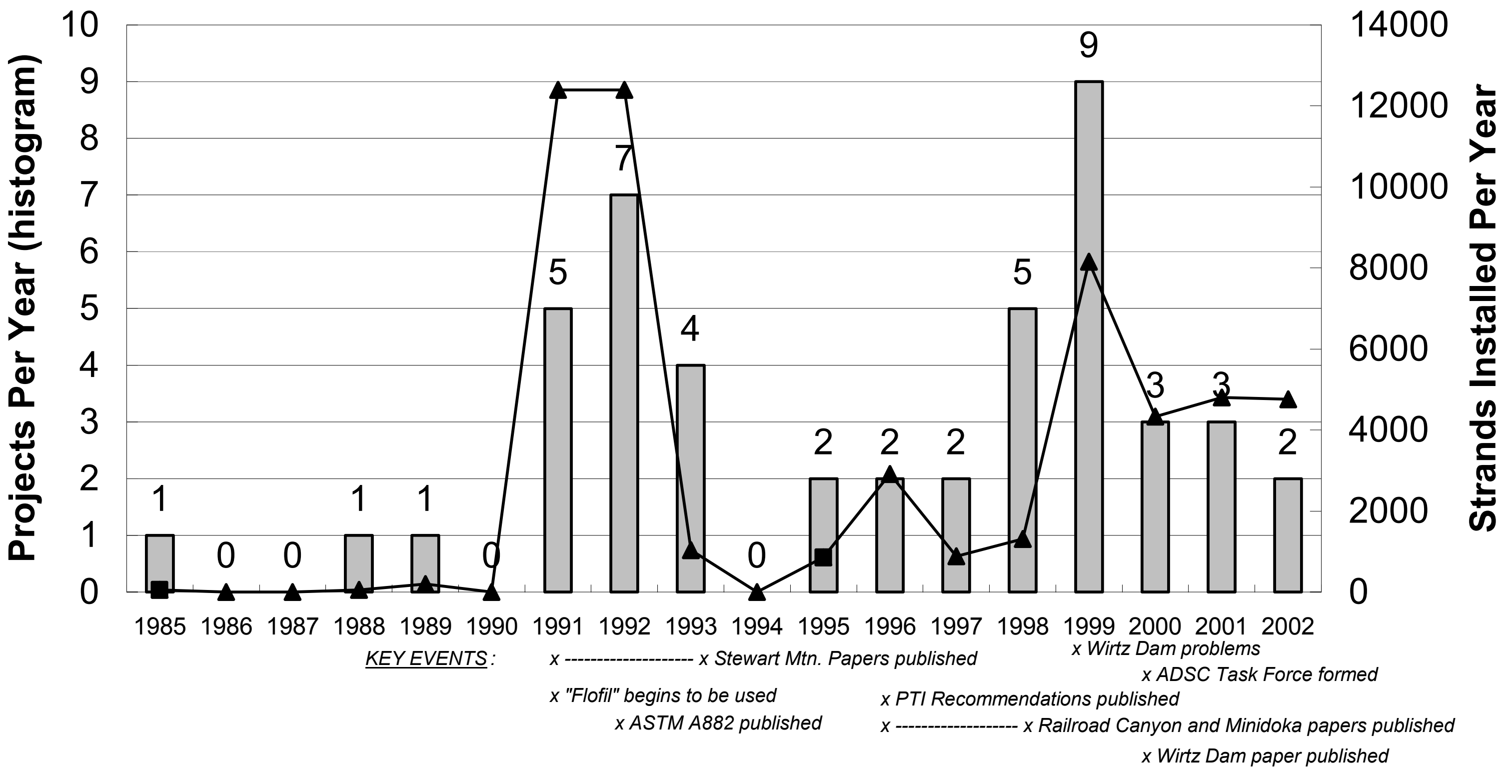
Table 2. Summary of Data from Anchor Projects Using Epoxy Protected Tendons (continues).

Year (No. of jobs)	Project Name	No. of Tendons	No. of Strands Per Tendon	Total No. of Strands	Inclin-ation	No. of Grouting Stages	Post Tensioning Supplier
2002 (2) to date	Golden Gate Bridge, CA	138	7-46	3652	Vertical	Two	DSI
	Rocky Creek Dam, SC	30	37	1110	Vertical	Two	LTI
2001 (3)	Santeetlah Dam, NC	13	59	767	Vertical	Two	LTI
	Rhodhiss Hydro, NC	55	35 – 58	2500 approx.	Inclined	Two	LTI
	Benicia Martinez Bridge, CA	44	35	1540	Vertical	Two	DSI
2000 (3)	Cowan's Ford, NC	73	54	3942	Inclined	Two	LTI
	Big Creek Pier, CA	8	21	168	Vertical	Two	CTS
	Carquenez Bridge, CA	8	28	224	Vertical	Two	CTS
1999 (9)	Lookout Shoals, NC	15, 9	37, 54	1041	Both		LTI
	Big Eddy Dam, ON	29	58	1682	Vertical		DSI
	High Rock Dam, NC	28	37 – 58	1400 approx.	Both	Two	DSI
	Pacoima Dam, CA	8	20	160	Inclined	Two	DSI
	Gaviota St, Long Beach, Ca	14	3 – 4	50 approx.	Inclined		DSI
	Two Ribbon Bridges, CA	48	18	864	Inclined	Two	CTS
	Bixby Creek Bridge, CA	32	27	864	Vertical	Two	CTS
	Wirtz Dam, TX	78	Up to 27	2000 approx.	Inclined	Single	CTS
	Fern Canyon Bridge, CA	4	24	96	Vertical	Two	CTS
1998 (5)	Tolt River Dam, WA	6	58	348	Vertical	Two	CTS
	Santeetlah Dam, NC	6, 2	44, 57	378	Both	Two	LTI
	Little Quinnesec, WI	5, 6	14, 19	184	Vertical	Two	CTS
	Big Creek Bridge, CA	12	15 to 28	250 approx.	Vertical	Two	CTS
	Cerritos Drive Laguna, CA	19	2, 7, 8	150 Est.	Inclined		DSI
1997 (2)	Minidoka Dam, ID	7	26	182	Vertical	Two	DSI
	Pardee Dam, CA	48	10 – 18	700 approx.	Inclined	Single	CTS
1996 (2)	Railroad Canyon Dam, CA	9 6	48 27	594	Vertical		DSI
	Yates Dam, AL	38, 6, 2	54, 36, 24	2316	Vertical	Two	LTI
1995 (2)	Saluda Dam, SC	5 10	37 17	355	Both	Two	LTI
	Carmichael Falls Hollow Dam, ON			Assume 500			DSI

Table 2. Summary of Data from Anchor Projects Using Epoxy Protected Tendons (concluded).

Year (No. of jobs)	Project Name	No. of Tendons	No. of Strands Per Tendon	Total No. of Strands	Inclin-ation	No. of Grouting Stages	Post Tensioning Supplier
1993 (4)	Lower Bonnington Dam, BC	26	26	676	Vertical		DSI
	Upper Bonnington Dam, BC	16	12	192	Vertical		DSI
	Buck Dam, VA	13	9 – 12	140 approx.	Vertical		VSL
	Kingston Ferry Terminal, WA	3	9	27 approx.	Vertical		DSI
1992 (7)	Martin Dam, AL	63	36 54	3000 approx.	Vertical	Two	LTI
	Oswego Falls, NY	32	15	480	Vertical	Two	LTI
	Upper Occoquan Dam, VA	56	20 – 53	2000 approx.	Vertical		DSI
	Occoquan Dam, VA	47	41 – 54	2500 approx.	Vertical		DSI
	Byllesby Dam, VA	8 12 56 4 2	3 24 32 34 36	2312	Inclined	Two	DSI
	Saluda Dam, SC		43	Assume 500			DSI
	Corra Linn Dam, BC	107	15	1605	Vertical		DSI
1991 (5)	Corra Linn Dam, BC	11	12	132	Vertical		DSI
	Stewart Mountain Dam, AZ	62 22	22 28	1980	Mainly inclined	Two	DSI
	Mathis Dam, FL	34	53	1802	Vertical		LTI supplied hardware. Owner assembled tendons.
	Burton Dam, VA	104	54	5616			
	Lloyd Shoals Dam	53	54	2862			
1989 (1)	L.A. Library, CA	20	9 – 12	200 approx.	Inclined		DSI
1988 (1)	Phoenix, AZ	13	4	52	Inclined		DSI
1985 (1)	Malibu, CA			Assume 50	Inclined		DSI

Notes:
1. Gaps in this table represent data to be acquired.
2. CTS = Con-Tech Systems; DSI = Dywidag Systems International; LTI = Lang Tendons, Inc.
3. All data subject to confirmation.



KEY TO GRAPH:

- Histograms show number of projects per year
- Strands installed per year:
  - ■ Approximated and/or estimated quantities
  - ▲ Quantities determined more closely

Figure 1. Epoxy protected strand usage for prestressed anchor applications, United States.

price being linked directly to the provision of the tendon and its hardware (i.e., $15 to 23 million). Figure 1 does illustrate, however, a smaller but relatively constant use of epoxy coated strand, following its peak of 9 projects in 1999.

In contrast, Kido (2002) notes that in Japan, Sumitomo Electric Industries Co., Ltd. started using epoxy protected strand ("Flotech") in 1991, the main applications being for ground anchors and post tensioned bridges. Statistics through 2000 on over 700 projects are summarized in Table 3.

Table 3. Data on Japanese usage of epoxy protected strand in ground anchors.

YEAR	NUMBER OF PROJECTS
1991	1
1992	3
1993	1
1994	0
1995	6
1996	17
1997	47
1998	89
1999	266
2000	303
Total	703 projects for a total of 606,000 lin. m.

Note: "Super Flotech" introduced in 1999 and now dominates usage.

Forty-three of these projects involved dam stabilization. At an average of 20 m per strand, one may assume that a total of around 30,000 strands have been installed, stressed, and locked off. There are no reports of problems in the short or long term. A few projects (for bridges) have been undertaken in Korea and the Philippines. No other foreign applications have been recorded to date.

REVIEW OF PUBLISHED DATA

Since 1991, there have been numerous publications on aspects of the use of epoxy protected strand, mainly in the form of project case histories. These papers in fact provide details on 23 projects. A close examination of the case history data reveals a very interesting trend (Table 4), in that of the 23 projects that were detailed in any way:

Table 4. Summary of published case history performance characteristics.

PROJECT	YEAR	REPORTED PROBLEMS	COMMENTS
Stewart Mountain Dam	1991	No	Acceptable long term performance confirmed by monitoring
Mathis Dam	1991	Yes	"Excessive creep" reported
Martin Dam	1992	No	Special testing used to ensure acceptability
Byllesby Dam	1992	Yes	30% slippage on first three anchors due to misalignment and cleanliness issues.
Occoquan Dam	1992	Yes	Strand slippages on early anchors due to grout in wedges; excessive creep.
Saluda Dam	1995	No	–
Railroad Canyon Dam	1996	No	Special wedges used.
Alton Clark Bridge	1995	Yes	Early strand slippages, plus corrosion under epoxy (Flo-Bond).
Pardee Dam	1997	No	"Previous problems" referred to.
Minidoka Dam	1997	No	"Previous problems" referred to in paper relating to other projects.
Tolt River Dam	1998	No	"Minor flaking" above wedges; 2 strands slipped.
Lake Quinesec Dam	1998	No	–
Big Creek Bridge Piers 1 and 3	1998	No	–
Santeetlah Dam	1998	Yes	One strand on a vertical anchor slipped.
High Rock Dam	1999	No	–
Ribbon Bridges	1999	No	–
Bixby Dam	1999	No	–
Fern Canyon	1999	Yes	Strand slippages.
Wirtz Dam	1999	Yes	Strand slippages.
Lookout Shoals Dam	1999	Yes	Strand slippages, and corrosion concerns.
Pacoima Dam	1999	?	?
Cowan's Ford Dam	2000	Yes	Strand slippages.
Big Creek Bridge Pier 2	2000	No	–
Carquenez Bridge	2000	No	–

- Seven reported strand slips through the wedges on a limited number of early tendons.
- One other reported "excessive creep" (which could, however, have been due to the inherent properties of the material, inaccuracies in load measuring and/or slippage of one or more strands after Lock Off).
- At least three took careful preemptive steps (or special monitoring) to successfully avoid short and long term problems.
- Two referred to "previous problems" having been reported on other projects.
- In addition, the author is aware that examples of strand slippage at lock off were noted (but not published) on a few strands at Stewart Mountain, Tolt River, and High Rock Dams: all simply remediated by thorough cleaning of the wedges and their seats.

The following conclusions may be drawn:

1. "Excessive" short term creep, relative to contemporary PTI Recommendations (1986) for bare strand, was first recognized in 1991, but was rationalized after laboratory testing, first described in 1994 (Bonomo).
2. Projects undertaken with strand manufactured in 1999 and/or 2000 seem to have had most slippages, following initial problems in the early 1990s, possibly due to stressing techniques.
3. Regarding those projects where strand slippages were recorded, these were typically only found during the "learning curve," i.e., on the first few anchors stressed. For example, wedges contained grout, rust, or other debris, and the importance of accurate alignment was not fully appreciated. Problems were most prevalent where the work was conducted by contractors using the material for the first time. Modifications to construction/stressing techniques, allied to intensive monitoring were successfully implemented, although at Wirtz Dam the problems were more pervasive and took longer to resolve.
4. It is likely that the problem has been more widespread than realized and that individual strand slippages have simply not been recognized (or recorded) by site personnel. Furthermore, "excessive creep," as measured on an entire tendon 24 or 72 hours after lock-off may in fact <u>not</u> have been the natural, gradual phenomenon participated in by all strands. Rather a loss of 2 or 3% of total tendon load in that period may equally have been caused by sudden slippage of 1 or 2 strands in a large, multistrand tendon, due to lock off problems.
5. It must be realized that the actual number of strands recorded as having slipped through the permanent wedges is a very small percentage of the total number of strands installed (perhaps about 0.1 to 0.2%). However, the technical, financial, and contractual impacts arising from the resultant project delays, and the general level of suspicion regarding the installed anchors are disproportionally high.
6. In virtually every case, the failures have been ascribed to inefficient seating of certain designs of wedges, i.e., their inability to quickly and uniformly bite through the epoxy and firmly engage the underlying steel. A detailed review of the literature dealing with the projects, and the forensic testing conducted in association, leads to defining certain broad groups of causes. It would seem that on any given project, failure is a combination of some or all of these individual factors, in proportions which cannot always be determined. Critical variations in aspects of material quality and construction processes can create a marginal environment on any given project wherein even small or otherwise unimportant details can prove sufficient to catalyze a slippage. In other words, the material and its associated lock off hardware are not as forgiving as bare strand to site practices and so special steps and care must be taken to assure reliable performance. Broadly speaking, the causes of problems may be summarized as follows:

    1. The nature of the product itself – being epoxy coated and filled, there will always be a tendency for higher short-term load loss to occur due to the

plastic properties of the coating, even under the best of circumstances (as acknowledged by PTI, 1996). This can be accommodated by revising short term creep acceptance criteria, and by two-stage grouting. Also the higher creep losses require their own acceptance criteria, and can actually be beneficial for the long term performance of the anchor. The initially reported creep losses will reduce the later occurring relaxation losses proportionally, allowing a higher design load, closer to the one for bare strand.

2. Manufacturing variations in the product – variations in epoxy thickness, homogeneity ("foaming" has been discovered on one company's product from 1999 and 2000), adhesion to the steel, and adhesion of grit to epoxy, will each affect lock-off effectiveness. Also "holidays" in the epoxy coating (apparently also related to foaming) can also create gaps in the corrosion protection which will permit the steel to corrode and thus further impact epoxy adhesion. Repair of such defects can be done on site but is tedious and costly, and is impractical if steel corrosion has already begun. (Corrosion will further reduce the epoxy-steel adhesion.)
3. Tendon and anchor geometry – uneven seating of the individual wedge parts may occur due to "differential" friction during multistrand loading. This is exacerbated in inclined tendons where strands have not been completely straightened prior to grouting, in tendons which have been poorly sorted (with spacers/centralizers) in their free lengths, and in anchors where primary grouting has been conducted to within 10 feet of the top anchorage plate prior to stressing. Primary grouting should not be conducted within 35 feet of the head.
4. Contamination of wedges and wedge holes – corrosion and dirt can build up on these vital components in the period between tendon installation and stressing. This is particularly significant in humid, dam environments, and is worsened by situations where inclined spillway anchors are inundated after installation. Such critical interfaces must be cleaned and lubricated prior to stressing. Also grit from the coating can clog wedge teeth if left in place during Performance Testing, further acting to prevent the essential "bite through" occurring into the steel. Thus final wedges should be placed only before the lock off process.
5. Misalignment – it is essential that all the stressing components, from tendon to upper gripper wedges are collinear, so eliminating the possibility of lateral loads preventing uniform and quick wedge seating.
6. Inappropriate anchor components – it is expressly recommended now not to strip the epoxy in the stressing tails to allow the use of "conventional" bare strand wedges in the top anchorage. Special wedges designed to reliably bite through the coating and into the steel strand, and special wedge plates – all free of dirt and dust, and well lubricated – must be used.

DUTIES AND RESPONSIBILITIES OF THE RESPECTIVE PARTIES

The author believes that the responsibility for the past problems the industry has encountered should be shared by all parties – if not necessarily equally. At least one strand manufacturer has not consistently produced a material that has met applicable codes and standards, or, more importantly, can withstand the rigors of well-known field conditions. Owners have perhaps been over eager to accept the financial benefits the product can afford, but have undervalued the concomitant risks. Designers have not been systematically pragmatic or informed about load loss issues and have not specified realistic acceptance criteria. Post tensioning companies that assemble tendons have occupied a pivotal position (technically, financially, and contractually) between manufacturer and contractor, but until recently, the majority has not consistently exerted the industry leadership their knowledge and experience would merit. Contractors have attempted to blame the other parties for problems found in the field while at the same time have made few efforts to adjust and enhance their construction methods to sensibly accommodate the special implications of the use of this material. Codes, standards, and recommendations have not comprehensively protected the goals of all parties. However, it is equally clear that the current reassessment of the issues has forged a new awareness in the industry, which, if appropriately exploited, can lead to mutual benefit.

Anchor Industry in General

1. Be aware of the types of problems which have occurred when using the material and have cognizance of remedial measures, options, or alternatives available. Also realize that different post tensioning systems exist and may provide different levels of performance.
2. Take a systematic and pragmatic view of the risk/benefit issues involved in the selection of the corrosion protection system, for each project.
3. Share fully and honestly all relevant experiences (good and bad) in an appropriate forum (e.g., ADSC Epoxy Coated Strand Task Force).
4. Promote and support the highest practical quality of manufacture and application via appropriate testing, and through revision and subsequent conformance with relevant recommendations and standards (e.g., ASTM A882, PTI, 1996). In this regard, it must be realized that a materials standard such as ASTM A882 will not cover handling and construction-related practicalities. The new supplement to the PTI Recommendations will address such issues.

Strand Manufacturer

1. Provide a consistent and reliable product conforming to all relevant codes, standards, and recommendations.
2. Knowing fully the "end use" of the product in such cases, provide all technical support to its clients in the development of appropriate tests and QA/QC methods (e.g., an adhesion test).

3. Immediately notify industry of any significant changes in the materials or details of manufacture which may potentially influence the product's ability to consistently satisfy project requirements.

Project Owner*

1. Even as a "non-specialist" relying on the advice of others, become in advance, cognizant of the state of industry thinking.
2. Ensure that the highest standards of site inspection are provided, and that the supervisory personnel involved have clear mandates as to their limits of authority regarding issues in non-conformance to the specification.
3. Provide an unbiased forum to help resolve any issues which may arise, and be prepared to provide sponsorship of any forensic efforts which may be required. (In this regard, the attitude of the Lower Colorado River Authority during and after the problems at its Wirtz Dam, has set the industry standard.)

Anchor Designers and Specifiers

1. Where allowed by the Owner, offer Bidders the option of epoxy protected strand, or corrugated sheathed tendons – price and performance to decide.
2. Specify two-stage grouting (i.e., to ensure that the strand is also bonded by grout in the free length – a minimum length of 35 feet of the tendon).
3. Specify special standards of care during tendon assembly, transportation, installation, grouting, and stressing especially for inclined anchors. In particular, the absolute cleanliness of the wedges and their anchor head pockets must be specified (especially for inclined anchors subjected to running water prior to stressing) together with appropriate use of spacer/centralizer units in the free length also.
4. Clarify precisely the liability of each party involved on the project, relative to the use of the product.
5. When assessing short and long term performance acceptance levels, be cognizant of the higher creep and relaxation losses inherent to epoxy protected strand. Specify short and long term load monitoring in excess of the minimum recommended by PTI.
6. Ensure that close and empowered independent site inspection is provided.
7. Specify exactly what will be expected of the contractor in event of "incidents."

Post Tensioning Companies that also Assemble Tendons

1. For every delivery of strand, secure full written warrantees from the supplier that the product is in conformance with all relevant codes, standards, recommendations, and specifications.

---

* For the sake of this listing, oversight agencies, such as FERC, are deemed included.

2. Obtain from the manufacturer any and all special test data (e.g., pullout tests, adhesion tests) which are required by the specification and/or the contractor, on a project-specific basis.
3. Exercise special care in the assembly, and transportation of the assembled tendons to avoid significant damage to the coating.
4. Provide only anchorage hardware which is fully appropriate to the material and the project conditions.
5. Provide only anchorage hardware which is fully appropriate for the stressing systems and methodologies.
6. Observe the provisions of all relevant codes, standards, recommendations, and specifications.

Anchor Contractor

1. Obtain all relevant certification and test data from tendon assembler, as required by the specifications and by the specific project requirements.
2. Be aware of all the potential causes of problems, and develop site practices to preempt them (from receipt of tendon to final anchor acceptance).
3. Observe the provisions of all relevant codes, standards, recommendations.
4. Observe the requirements of the specifications, as a minimum acceptable standard.
5. Provide only knowledgeable and experienced stressing personnel who have executed such work previously. (If not available, ensure that appropriate training or resources are obtained via the post tensioning companies)
6. Maintain full, frank, and informed technical dialogue with all parties at every phase of the project (from preconstruction submittals to final anchor report).
7. Inspect all tendons upon delivery to site so that any problems can be immediately referred to the tendon supplier. Thereafter, any "flaw" observed during actual tendon handling on site and installation will be the technical and financial responsibility of the contractor.

FINAL REMARKS

This paper is written with the benefit of long hindsight, and so illustrates certain shortcomings in the way we in the anchor community have collectively addressed certain issues. While there is no systematic reason to doubt the ability of the anchors installed to date to satisfy the owners' goals – there is an almost overwhelming degree of redundancy in certain aspects of dam anchor systems – there is a clear need to improve current practice to eliminate the costly and controversial problems which have affected the construction phase of several projects to date.

Awareness of problems is the first major step in solving them, and in this regard, the activities of the Task Force of ADSC, have provided vital industry leadership. In addition to facilitating papers such as this, the Task Force is exerting an active and consistent influence on the PTI Recommendations, via the upcoming supplement, and upon the current version of the ASTM standard (ASTM A882/A882-96). As an example, the following items are understood to be approved for future incorporation (inter al.) in the revision of the ASTM standard:

1. Only epoxy coated and filled strand is recommended for use in anchors.
2. Filled strand shall have relaxation losses of not more than 6.5% after 1000 hours when initially loaded to 70% GUTS.
3. "Disbonding" is a term introduced to describe loss of adhesion between epoxy and steel.
4. Manufacturer to provide creep data on strand (at 80% GUTS) over periods of 10 minutes, 1 and 3 hours, in combination with relaxation test data.

A change in the permissible range of epoxy thicknesses from 25-40 mils to 15-40 mils is still pending. The thinner coating has been proven to afford adequate corrosion protection, seems to have a better adhesion to the strand, and is more easily gripped by the wedges.

Readers of this paper are strongly encouraged to provide critical comment and factual input so that a full and accurate document will ultimately be produced. Such a document will hopefully be beneficial to the interests of all parties in the dam anchor industry.

REFERENCES AND BIBLIOGRAPHY

American Society for Testing and Materials. (2001). Specification A882/A882M-01 Standard Specification for Epoxy-Coated Seven-Wire Prestressing Steel Strand, West Conshohocken, PA.

Aschenbroich, H. (2000). "Experiences and Observations Using Epoxy Coated Flo-Fill Flo-Bond 0.6" 270 ksi Strand for Permanent Rock and Ground Anchors." ADSC Seminar, October 25, Dallas, TX.

Baldwin. (2001). Personal communication, Nicholson Construction Co., Bridgeville, PA, January.

Banna, H. and K. Lilley. (2001). "Pacoima Dam after the 1994 Northridge earthquake: design, installation , and maintenance of high strength steel rock anchors, epoxy injection and extensometers." Proceedings of the Annual Conference, Association of State Dam Safety Officials, Snowbird, UT, September 9-11, 11 p.

Bianchi, R.H. and Bruce, D.A. (1993). "The Use of Post Tensioned Anchorages on the Arch Portion of Stewart Mountain Dam, Arizona." ASCE Specialty Conference on Geotechnical Practice in Dam Rehabilitation, N.C. State University, Raleigh, N.C., April 25-28, pp. 791-802.

Bogdan, L. (2001). "Post Tensioned Anchors Using Epoxy Coated Strand for Rehabilitation of Concrete Dams." *The Future of Dams and their Reservoirs*. 21st Annual USSD Lecture Series, United States Society on Dams, Denver, CO, July 30-August 3, pp. 681-692.

Bogdan, L. (2001). "The Use of Epoxy Coated Strand for Post Tensioned Anchors." *Foundation Drilling*, ADSC, September/October, pp. 23-34.

Bogdan, L., T. Feldsher, and D. Moody. (1996). "Rehabilitation of Railroad Canyon Dam." *Foundation Drilling*, ADSC. pp. 13-14.

Bonomo, R. (1994). "Permanent Ground Anchors Using Epoxy Coated Strand." *Foundation Drilling*, ADSC, March/April.

British Standards Institution. (1989). "Ground Anchorages." BS8081. BSI, London, England.

Bruce, D.A. (1989). "An Overview of Current U.S. Practice in Dam Stabilization Using Prestressed Rock Anchors." 20th Ohio River Valley Soils Seminar, Louisville, KY, October 27, 15 pp.

Bruce, D.A. and L.K. Nuss. (1992). "Anchoring Stewart Mountain Dam Against Seismic Loadings." Proc. 45th Canadian Geotechnical Conference, Toronto, ON. October 26-28, paper 25, 11 pp.

Bruce, D.A., Fiedler, W.R., Scott, G.A. and Triplett, R.E. (1992). "Stewart Mountain Dam Stabilization." USCOLD Newsletter, 97, (March) pp. 6-10.

Bruce, D.A.. (1997). "The Stabilization of Concrete Dams by Post-Tensioned Rock Anchors: The State of American Practice," *Ground Anchorages and Anchored Structures*, Proceedings of the International Conference, Institution of Civil Engineers, London, U.K., Thomas Telford, Ed. by G.S. Littlejohn, March 20-21, pp. 508-521.

Buhac, H.J., and R. Baldwin. (1994). "Cutting Dam Stabilization Costs through Innovation," *Civil Engineering News*, Vol. 5, No. 12, January, p. 33.

Frithiof, R., and P. Krumm. (2000). "Wirtz Dam Post Tensioned Anchoring Project Issues Affecting the Performance of Epoxy-Coated Tendons," *Dam O&M Issues* – The *Challenge of the 21st Century*, Twentieth Annual USCOLD Lecture Series, Seattle, WA, July 10-14.

Kido, T. (2002). Personal communication. Sumiden Wire Products, Stockton, CA, February.

Krumm, P. "Issues Affecting the Performance of Epoxy-Coated Tendons." ADSC Seminar, October 25, Dallas, TX.

Lang, J.C. (2000). "Technical and Contractual Issues for Epoxy Coated Strand Anchor Jobs," ADSC Seminar, October 25, Dallas, TX.

Leamon, T.D., and L.F. Dunlap (1994). Source unknown.

Marsh, S.G., T.B. Feldsher, and L.I. Bogdan. (1997). "Rehabilitation of Railroad Canyon Dam." Proc. of the Association of State Dam Safety Officials, 14th Annual Conference, Pittsburgh, PA, September 7-10, Compact Disc.

Nierlich, H. and D.A. Bruce. (1997). "A Review of the Post-Tensioning Institute's Revised Recommendations for Prestressed Rock and Soil Anchors, *Ground Anchorages and Anchored Structures*, Proceedings of the International Conference, Institution of Civil Engineers, London, U.K., Thomas Telford, Ed. by G.S. Littlejohn, March, 20-21, pp. 522-530.

O'Brien, M. (2000). "Stressing Epoxy Coated Strand Anchors: The DSI Experience," ADSC Seminar, October 25, Dallas, TX.

Plizga, A.W., P.F. Shiers, S.W. Schadinger, and J. Lyon. (2001). "Installing High Capacity Rock Anchors to Meet Stability Requirements." *The Future of Dams and their Reservoirs*. 21st Annual USSD Lecture Series, United States Society on Dams, Denver, CO, July 30-August 3, pp. 125-136.

Post Tensioning Institute (PTI). (1996). "Recommendations for prestressed rock and soil anchors." Post Tensioning Manual. Fourth Edition. Phoenix, Arizona. 41 p.

Trojanowski, J., W.R. Fielder, L.J. Bogdan. (1997). "Stabilization of Minidoka Dam Using Epoxy Coated Strand Rock Anchors." *Dam Safety '97*. Proceedings of the 14th Annual Conference, Association of State Dam Safety Officials, Pittsburgh, PA, Compact Disk, September 7-10.

Tucker, T. (2001). "Saluda Hydro Station – Stability Remedial Work." Project Description and Specifications. Personal communication, August.

Wagner (2000). "The Status of Epoxy Coated Strand at Florida Wire and Cable." ADSC Seminar, October 25, Dallas, TX.

Appendix 1. Critical Analysis of Published Data on Projects with Epoxy Coated Strand (continues).

SOURCE AND DATE	PERSPECTIVE	TYPE OF PAPER	SIGNIFICANCE/KEY ISSUES RELATING TO EPOXY COATED/FILLED STRAND
Bruce et al. (1991 through 1993 several)	Contractor and Owner	Case history of Stewart Mountain Dam, AZ (Construction: 1991)	• Non-filled strand used, on first major epoxy strand project, strongly promoting use. • Vertical and inclined anchors installed, two-stage grouting. • Long term monitoring (90 days) showed no systematic problem. • A few strands slipped – judged not significant at time.
Leamon and Dunlap (1994)	Owner/ Designer	Case histories of (Mathis Dam, AL) (1991 – 1992) Martin Dam, AL (1992 – 1993)	• In 1991, FERC insisted upon filled strand being used. • "First indication" of short term creep problems at Mathis, also evaluated at Martin, on systematic basis. • Hypothesis evolved that creep was proportional to strand free length.
Buhac and Baldwin (1994)	Owner and Contractor	Case history of Byllesby Dam, VA (1992)	• Paper strongly promotes use. • However, later personal communication (2001) confirms first three anchors had slippage on 30% strands (arguably due to misalignment of hole and tendon, and, corrosion of components in long submerged period prior to stressing).
Bonomo (1994)	Tendon Assembler	Overview of history, applications, and issues	• Provided history of usage. • Highlighted creep, relaxation and lock off issues. • Discussed construction-related problems. • Extremely supportive of the use of the material, with appropriate controls, allowances, and methodologies.
Tucker (2001)	Contractor	Case history of Saluda Dam, SC (1995)	• No problems recorded.
Marsh et al. (1996); Bogdan et al. (1996)	Designer, Contractor, and Assembler	Case history of Railroad Canyon Dam, CA (1995 – 1996)	• Promoting use of product. • Special wedges used. • Awareness of need for special stressing modifications clear. • Long term monitoring conducted. • "Creeping suspicions" about product reported "elsewhere in the literature." • No problems recorded in the case history, but reportedly did occur.
Trojanowski et al. (1997)	Owner, Designer, and Assembler	Case history of Minidoka Dam (1997)	• "Creep within the epoxy coating itself has been a concern during tensioning," based on data from other sites. • Specification modified based on tests by FWC (1993) and Recommendations of PTI (1996) for creep. • No problems recorded.

Appendix 1. Critical Analysis of Published Data on Projects with Epoxy Coated Strand (continues).

Source and Date	Perspective	Type of Paper	Significance/Key Issues Relating to Epoxy Coated/Filled Strand
Frithiof and Krumm (2000)	Owner and Contractor	Case history of Wirtz Dam, TX (1999)	• Major strand slippages recorded on one-stage grouted, inclined tendons (9 strands). • Site tests confirmed unequal strand loading due to strand misalignment/bending in hole. • Laboratory tests confirmed variations in coating thickness and quality (plus "holidays"). This was the first paper to highlight significant problems with the quality and consistency of the material itself (could explain many prior problems) leading to major concerns about coating adhesion to steel and efficiency of its long term protection. • The problems experienced on this site precipitated the current industry initiative.
Aschenbroich (2000)	Assembler	Several summary case histories (1995 – 2000); Pardee Dam, CA (1995)	• "Problems on previous projects" referred to. • Despite variations in product, no problems encountered: new anchorage components developed. • Success encouraged subsequent Caltrans' use on bridge structures.
		Tolt River Dam, WA (1998)	• Some epoxy "flake off" above wedges noted (2 strands) • No slippage or excessive creep.
		Little Quinnesec Dam, WI (1998)	• No problems reported.
		Big Creek Bridge, CA (1998)	• No problems reported.
		Ribbon Bridges, CA (1999)	• No problems reported.
		Bixby Creek Bridge, CA (1999)	• No problems reported.
		Wirtz Dam, TX (1999)	• Severe problems with wedge seating (due to "differential friction," and variations in material properties). • Following adjustments to construction methods, no short- or long-term problems.
		Fern Canyon Bridge, CA (1999)	• On one anchor, 4 of 24 strands pulled. • Same time as Wirtz Dam issues.
		Big Creek Bridge, CA (2000)	• No problems reported.
		Carquenez Bridge, CA (2000)	• In light of previously encountered problem, Owner revised stressing procedure.

Appendix 1. Critical Analysis of Published Data on Projects with Epoxy Coated Strand (concluded).

Source and Date	Perspective	Type of Paper	Significance/Key Issues Relating to Epoxy Coated/Filled Strand
Wagner (2000)	Manufacturer	Brief overview of properties of material and related impact	• "It is well known" that short and long term creep and relaxation are higher, although the variation is not qualified. • Construction related issues important (e.g., differential friction, alignment, cleanliness). • Variability of product not discussed.
Lang (2000)	Assembler	Critical overview of technical and contractual issues. Plus, case history of Lookout Shoals and Cowan's Ford Dams, NC (1999 and 2000)	• 5 dams (1990-1995) used stripped epoxy and normal wedges. Subsequent 5 dams have used special epoxy wedges. • 4 of 24 anchors at Lookout Shoals and 9 of 73 anchors at Cowan's Ford had problems, mainly with slippage and/or excessive creep, but also with frequent "holidays." • Creep/slippage problems resolved by extra cleaning/lubrication of top anchorage components. • Recent product tests provide higher creep values than PTI Recommendations.
O'Brien (2000)	Assembler	Overview of corporate experience via summaries of case histories Occoquan Dam, VA (1992)	• "Some concern by designer" over long term performance. • Grout contaminated wedges caused explosive failure in first anchor only.
		Byllesby Dam, VA (1992)	• See Buhac and Baldwin (1994) above.
		Alton Clark Bridge, IL (mid 1990s)	• A "few" strands slipped due to misalignment in the tendon. • Rust was also reportedly found under the coating.
		High Rock Dam, NC (1999)	• Several strands slipped in first anchor over a period of "a few hours." • Components found to be corroded. After replacement, no further problems.
Plizga et al. (2001)	Owner and FERC	Case history of High Rock Dam, NC (1999)	• Slippage recorded on a few strands in first anchor. • Cause was contamination of head and wedges, although tendon alignment also queried. • 9 further strands explosively slipped at Test Load.
Bogdan (2001)	Assembler	Detailed overview of all aspects of product and its use	• Strongly promotes use of material if proper controls exercised on material production and construction techniques. • Material has a higher creep rate "for a short period of time immediately" after lock off. • Valid adhesion test still not developed.