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PART A

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Edited by

LI Shengcai
WANG Weiye
AN Ying

State Key Laboratory of Explosion Science and Technology
Beijing Institute of Technology
Beijing 100081
P. R. China

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Introduction of the Content

This monograph is the Proceedings of the 2010 International Symposium on Safety Science and Technology (2010 ISSST). Collected in this volume are 415 papers from twenty countries and regions. These papers cover the following aspects: Theories and Methods of Safety Science; Safety Assessment and Risk Analysis; Safety Monitoring and Supervision; Emergency Management and Evacuation; Public Security; Occupational Health and Human Behavior; Numerical Simulation of Fire; Fire Experiment and Property Research; Smoke Control; Fire Control and Extinguishing; Fire Extinguishing Agent and Fire Equipment; Explosion Performance and Safety of Hazardous Materials; Blast Safety; Gas Explosion and Safety; Leakage of Combustible and Toxic Materials; Safety of Chemical Reaction Tank and Pressure Vessel; Performance and Process of Burning; Work Safety in Coal Mine; Spontaneous Combustion in Coal Mine; Gas and Dust Control in Coal Mine; Coal, Gas and Rock Burst; Ventilation; Bridge Safety Engineering; Dam Safety; Fatigue, Lifetime and Reliability; Traffic and Transportation Safety; Construction and Building Safety; Slope Stability; Safety of Tunnel and Metro Construction; Safety Management; and Miscellaneous. Many novel research results on safety science and technology achieved during the last few years are mentioned in the proceedings.

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PREFACE

2010 International Symposium on Safety Science and Technology (2010 ISSST) is to be held in Hangzhou, Zhejiang Province, China, October 26–29, 2010. It is the seventh of this series, and the previous six international symposia were held in Beijing (1998 and 2000), Tai'an(2002), Shanghai(2004), Changsha(2006), and Beijing(2008) respectively.

2010ISSST is sponsored by China Occupational Safety and Health Association, and Beijing Institute of Technology, organized by the State Key Laboratory of Explosion Science and Technology (Beijing Institute of Technology) and China Jiliang University, and co-organized by Henan Polytechnic University. The principal ambition of the 2010ISSST is to promote the exchange of novel ideas through the close interaction of research groups from all Safety Sciences and Technologies.

The proceedings contains 415 papers contributed by 1057 authors and co-authors from twenty countries and regions which are: Australia, Belgium, Canada, China, France, Germany, Hungary, Italy, Japan, Korea, Malaysia, the Netherlands, Norway, Poland, Saudi Arabia, South Africa, Spain, Taiwan of China, UK and USA. The content of the proceedings have also been recorded in electronic form and provided on CDROM in color. I believe that the proceedings will benefit not only the participants of the meeting but also all of colleagues engaging in the research and development of safety science and technology.

I wish to thank Prof. FAN Weicheng of China and Prof. Ben ALE of the Netherlands for their outstanding and dedicated contributions as the symposium co-chairmen. Thanks are also given to the members of International Advisory Committee of the Symposium for their tremendous contributions, and to all the authors for their valuable papers.

In addition, I would like to express my sincere thanks to the staffs of the Editorial Department of *Journal of Safety and Environment* for their tireless efforts and outstanding services in the administration and preparation of the manuscript of the proceedings, to the staffs of Science Press for their diligence in publishing the proceedings.

Finally, I wish all participants a most enjoyable and informative experience.

冯长根

Dr. FENG Changgen

Executive Secretary of the China Association for Science and Technology

Professor of the Beijing Institute of Technology

Secretary General of 2010 International Symposium on Safety Science and Technology

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Part A

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THEORIES AND METHODS OF SAFETY SCIENCE

SECTION TWO
SAFETY ASSESSMENT AND RISK ANALYSIS

Forensic Engineering Investigation of Basketball Goal Support Failure

David S. KOMM, P.E., C.F.E.I.; Quent AUGSPURGER, P.E.; Hugh J. MCSPADDEN
Augspurger Komm Engineering, Inc., 3315 E Wier Ave., Phoenix, Arizona 85040, USA

Abstract.: This paper describes the forensic engineering analysis done to identify the probable cause of failure of one basketball goal support pole, positioned adjacent to a residential driveway in central Arizona. The abrupt failure of the pole portion of the goal system caused a fatality. This paper describes the collection of evidence, development of a probable scenario, and testing done to confirm the scenario. Major contributing factors reviewed included the manufacturer's instructions, site preparation, anchoring of the pole, and the actual installation. Metallurgy and other factors were also examined to identify the probable cause of failure.

Keywords: Basketball goal, vibration, corrosion, brittle failure, Failure Modes and Effects Analysis (FMEA).

1 General Comments.

Basketball is a sport enjoyed in many countries by many people, both as individuals and as members of a team, or even as observers. Multiple companies made single-pole basketball goal systems for consumer use, designed to be mounted into concrete footings. These systems have been sold across the nation, with some of the systems experiencing failures that resulted in personal injuries, and even in death.

Augspurger Komm Engineering Inc. became involved with this particular failure and the resulting investigation approximately 14 months after the date of the actual accident. This delay between the date of the accident and the involvement of Augspurger Komm Engineering, Inc. is more or less typical of many forensic investigations. The delay simply means it is necessary to work with evidence that may have been relocated to storage facilities, or which may exist only in photographs dating to the time of the incident. Such delays mandate the use of thorough and methodical steps in the systematic investigative process.

This forensic investigation lasted more than 25 months. Such length of time is not unusual because there is often an early phase when there is fairly intense work, followed by the slower progress of litigation, often requiring additional supporting information, and depositions, before the conclusion of the litigation.

2 Introduction

Approximately 14 months after the accident, a legal firm representing the plaintiffs in a wrongful death suit against the manufacturer of the basketball goal assembly hired Augspurger Komm Engineering, Inc. to determine the probable cause of failure of the pole. Event reconstruction was required, starting with the installation of the subject pole. The subject basketball pole, with the attached backboard, hoop and net, had been installed according to the manufacturer's instructions[1], including the use of a concrete footing, and concrete inside the lowest section of the three-piece pole assembly.

The installation was in the yard, several inches away from the concrete driveway at a Phoenix, AZ residence. The pole abruptly broke, falling away from the driveway and onto one person who was in the yard near the pole. This person was the fatality.

Weather conditions at time of the accident were typical for the time of year: late winter day, dry with clear skies and seasonal temperatures. Thus, the overall weather conditions on the date of the accident were not a contributing factor.

The position of the broken pole with reference to the house, yard and driveway is shown below in Photos 1a[2] and 1b[2].

Photo 1a[2]. Broken pole in yard.

Photo 1b[2]. Broken pole in yard.

3 Outline Of Steps Used In Event Reconstruction And Analysis

3.1 Observations of subject pole

Photos[2] taken on the day of the accident show the location of the fallen pole. The photos also show significant corrosion of the pole extending a few inches above the break, as well as the concrete filling the inside of the pole and the fact that it failed in a brittle manner.

Photo 1c[2]. Location Of Fallen Pole

Photo 1d[2]. Close-up Of Broken Pole, At The Break.

Close visual examination of the broken end of the subject pole was done, and showed the presence of the unreinforced concrete, as well as obvious thinning of the tube wall by corrosion (rusting).

Rusting of mild steel (an iron alloy) is the chemical conversion of the iron atoms into ferric oxide, through a reaction (oxidation) with water and/or atmospheric oxygen. The ferric oxide created is larger in volume than the original iron atoms from the alloy. The increased volume pushes the iron oxide (rust) away from the pole, forming layers of varying thickness that spall off the surface of the pipe, exposing new metal and starting the cycle over again, in a repetitive process.

A sample of the metal of the subject pole was submitted to a testing laboratory for analysis. The results[3] confirmed the metal is mild steel, ASTM alloy 1008.

Photo 2. Close-up View Of Subject Pole End, Showing Corrosion.

Measurement of the corroded portion of the subject pole was done in a pattern of every 0.125 inch axially, and every ten degrees circumferentially. Measurements began at a point approximately 2.5 inches from the uneven edge of the failed pole.

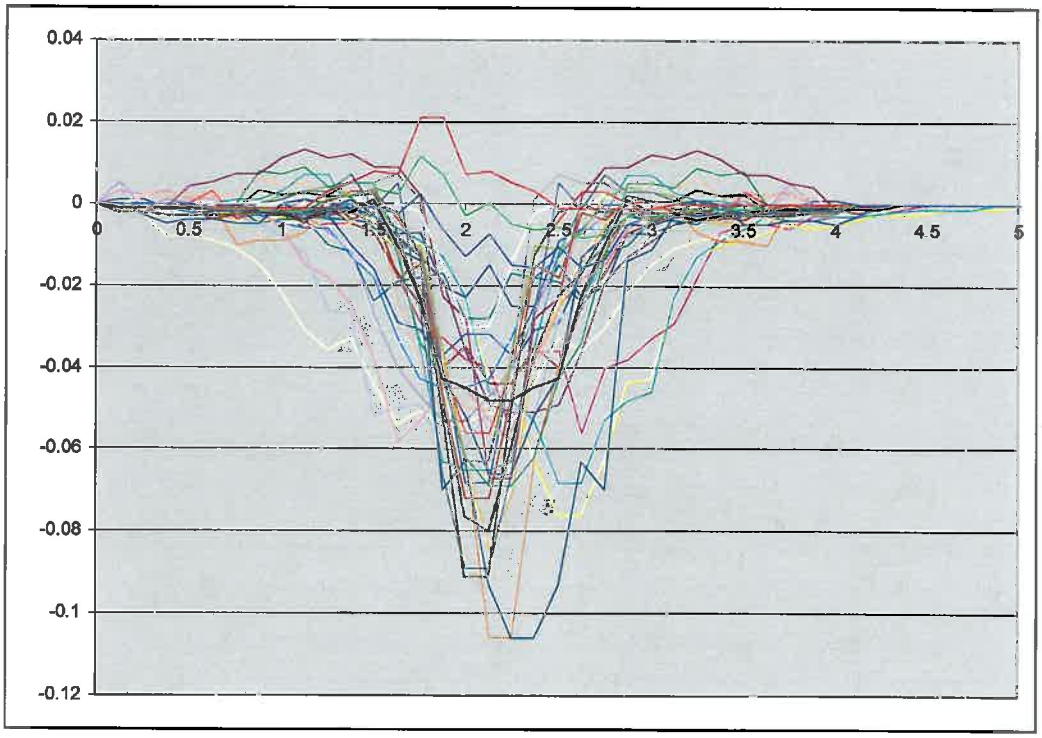

Figure 1. Plot Of Initial Measurements Of Missing Metal Of Pole.

Analysis of the raw data showed a sinusoidal variation of the remaining steel thickness. After allowing for rust on one or both surfaces of the tube as appropriate, the thickness of the remaining steel was calculated to be 0.004 to 0.034 inches. The following graph shows the change in wall thickness, as measured on the subject pole. The measurements have been "mirrored" to provide a probable profile above and below the break. The measurements clearly show a "necking" effect as well as the off-center (sinusoidal) variation of the remaining wall thickness

3.2 Comparisons Of Subject Pole With Exemplar And New Poles

An existing, still installed in the ground, pole was located and acquired as an example of a typical pole that that had been installed in concrete for a number of years. This exemplar pole is shown in the next two photos.

Photos 3a and 3b. Close-ups Of Exemplar Pole

The corrosion noted on this exemplar pole is very similar to that of the subject pole, and the pole metal was weakened enough that a portion of the tube wall offered little resistance to bending and possibly even tearing during the removal of the pole. In addition, the rust found on the broken surface of the concrete is evidence that the concrete was at least partially broken, if not totally broken before the pole was removed by Augspurger Komm Engineering, Inc.. The rust also suggest the possibility that the pole had corroded all the way through in places. The broken end of the pole was located flush with the concrete footing.

Another installed pole, shown in the following two photos, has corrosion in two places: (a) adjacent to the concrete base and (b) at the junction of the lower and middle pole segments.

Photo 4a. External Rust On Second Exemplar Pole

Photo 4b. Layers of Rust, Pushed Away From Pole Metal At The Joint Between The Lower And Middle Sections Of The Pole

General analysis of goal systems

A basketball goal system of the type that failed has one fixed end and one free end. The fixed end is where the pole is embedded in the concrete base. This embedment defines a node of the vibrating pole. Because the goal and backboard end of the system are free to flex when struck by a basketball, the length of the pole above the concrete base is a half-wavelength of the resonant frequency.

The kinetic energy transferred by the impact of the basketball against the backboard is absorbed at the point where the pole is restrained: the nodal point of the resonant frequency, at the surface of the concrete base.

This energy absorption creates at least three detrimental effects: (a) Weakening of the mild steel tube by repeated flexing; (b) Flaking or spalling of the rust layers formed by corrosion of the pole metal; and (c) Weakening and eventual breaking of the concrete inside the pole. The combination of these effects will eventually destroy the structural integrity of the pole, causing the goal system to collapse.

Consumer Product Safety Commission records[4] were obtained where poles had failed and injuries were caused by the failure. A record of a pole failure in Connecticut[5] was also obtained, where the person heard the pole vibrating and moved out of the way before the pole fell. Review of these records provided evidence that vibration was involved at the time of some of the failures. In addition, observation of goal systems in actual use showed flexing and vibration when the backboard was hit by a basketball. Installation instructions[1, 6-7], differed from manufacturer to manufacturer, -- one specifying the use of a length of steel reinforcing rod inside the concrete within the lower pole section, while a different manufacturer's instructions said nothing about such reinforcement.

A review of all documentation available, plus observations of the subject and exemplar poles, defined that successful identification of the cause of the failure of the subject pole required vibration testing of basketball goal systems with both reinforced and unreinforced concrete fills in order to compare the two sets of instructions. The first step in this testing was to measure the natural vibration frequency of new exemplar, concrete-filled poles.

Testing of poles

The testing of new poles used three-axis accelerometers to measure the vibration of the pole after the backboard was struck with a basketball. The resonant frequency of 3.34 Hz was measured by analyzing the records of approximately 20 impacts by a basketball.

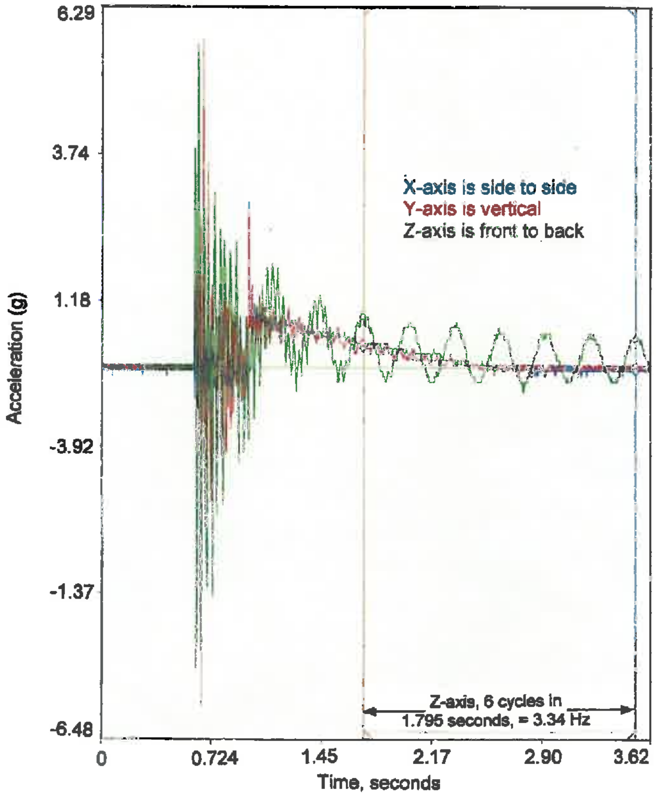

Figure 2. Graphical Output From Resonant Frequency Test.

In addition, the nominal deflection of the backboard was recorded with high speed video so that the deflection could be estimated. The deflection was found to be about one inch for a typical impact of a basketball with the backboard. Greater or lesser force with which the basketball strikes the backboard will not change the natural vibration frequency, but will only alter the amplitude of the vibration.

The major vibration observed is the "Z" axis, fore and aft, perpendicular to the face of the backboard. The "X-axis" is horizontally, parallel to the face of the backboard, and the "Y-axis" is the vertical axis. Only the Z-axis shows a relatively slow oscillation/vibration frequency. It is noted that there is a significant vibration in the Y-axis, vertically into the support pole. This vibration has the potential to rub the powder coating against the concrete on the outside of the pole, leading to erosion of the thin coating (typically only 0.002 to 0.0025 inches thick).[8,9]

A test method and structure was designed to subject new poles to approximately one inch of deflection at the resonance frequency. A pulley was attached at the top of the pole. An off-center weight was attached to the pulley. The pulley was belt driven by a direct current motor, adjusted to turn the pulley and weight at the resonant frequency. The observed total displacement of the top of the pole was about one inch, similar to the deflection caused by a basketball impact.

The upper range of age of installed poles was estimated at ten years. It was then assumed that the average use of the basketball goal system would be for one hour per week for ten years, and that the upper range of impacts by a basketball against the backboard would be 150 strikes per hour. This number of impacts was calculated to require slightly less than 39 hours of vibration at the resonance frequency of 3.34 Hz.

Three exemplar goal systems were prepared for testing to determine the effect of vibration on the concrete at the nodal point of the resonant vibration. The poles were mounted in 24-inch diameter concrete to the depth specified in the instructions.

After the vibration testing was complete, the goal systems were disassembled and the poles removed from the concrete bases with a tubular saw designed for cutting concrete. Once removed from the concrete anchor, the depth the tubes had been inserted into the concrete was marked and the concrete on the outside carefully removed.

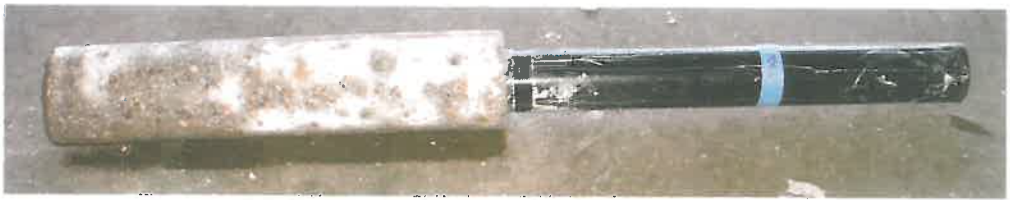

Photo 5a. Pole Section After Vibration, And Removal From Concrete Base.

This was followed by carefully making two longitudinally cuts at 180 degrees through the tube wall for the full length of the tubes. This allowed the tubes to be separated from the concrete filling without putting stress onto the concrete.

Photo 5b. Pole Sections After Longitudinal Cutting, But Before Opening The Sections.

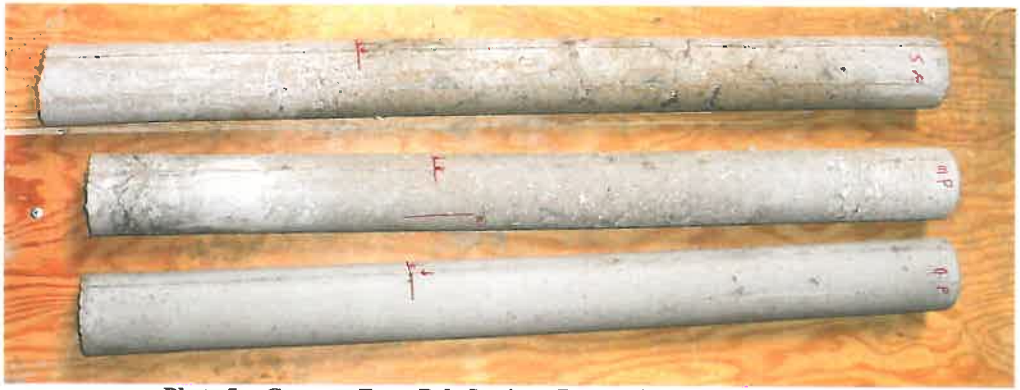

Photo 5c. Concrete From Pole Sections, Reassembled After Inspection.

Visual inspection confirmed all three concrete fillings were broken at a point corresponding to the depth of the outer concrete base. The concrete from each tube was in two pieces, with no bonding between the sections.

Four additional exemplar basketball goal assemblies (pole, backboard, hoop and net) were prepared for testing by machining the bottom section of the pole to approximate the wall thickness and the sinusoidal variation of thickness that was measured on the subject pole by providing a "necked down" section approximately two inches long, thinnest in the middle, with an off-center wall thickness of 0.004 to 0.034 inches.

The basketball goal systems were then assembled, including the concrete filling of the lower pole section. The poles were clamped in a rigid mount at the bottom end of the machined section as shown in Photo 6a.

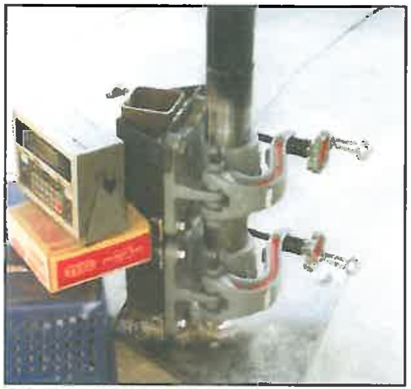

Photo 6a. Machined Exemplar Pole In Clamp, Prior To Test.

Two poles were tested for angular displacement prior to failure. One pole contained unreinforced concrete, and the other pole contained concrete reinforced with a 0.5-inch diameter steel reinforcing bar. The angular displacement was measured by a dial micrometer, and the degrees of bend calculated at intervals during the destructive testing. The testing was done by applying a tension load to the hoop of the goal until failure occurred

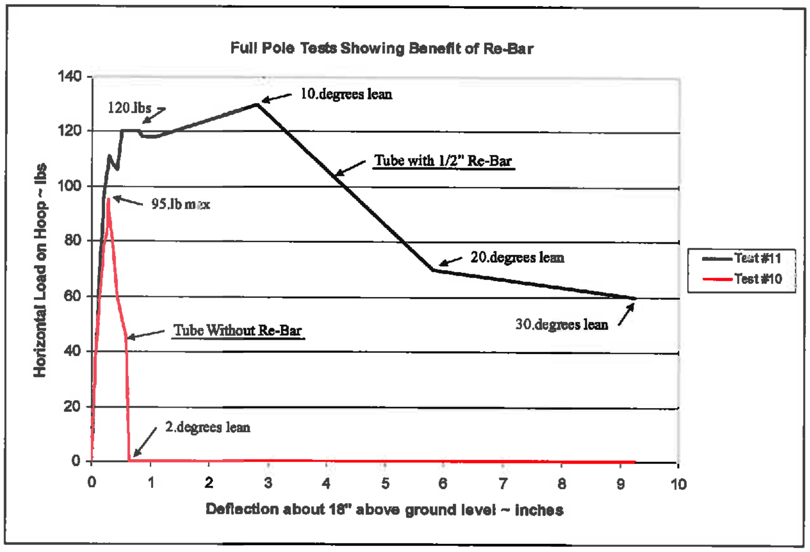

Figure 3. Applied Forces, Versus Inches Of Lean Of Pole

Two additional exemplar poles, one each with reinforced and unreinforced concrete were tested for the force required to cause the pole to fail. The tests to failure were done by pulling on the hoop of the goal. The base of pole was rigidly clamped at about 17 inches from end of pole, simulating a pole anchored in concrete. The pole diameter was machined to approximate or mimic the wall thicknesses and the sinusoidal variation of thickness that was measured on the subject pole by providing a "necked down" section approximately two inches long and thinnest in the middle, with an off-center wall thickness of 0.004 to 0.034 inches.

Tensile force was progressively applied to the hoop of the goal. Measurement of the force required was made with a strain gage load cell, monitored during the application of the tension tests. Failure occurred at the thinnest part of the machined section of the pole and the concrete broke with no reinforcing bar present in the concrete, shown in photos 6b and 6c.

Photo 6b. Machined Exemplar Pole Without Reinforcing Bar In Concrete, After Test.

Photo 6c. Close-up Of Failure Of Machined Exemplar Pole

When a reinforcing bar was used in the concrete, the pole was bent and broken, with the concrete also broken. But the reinforcing bar provided significant strength, keeping the two portions of the pole together and thereby preventing a total collapse of the pole.

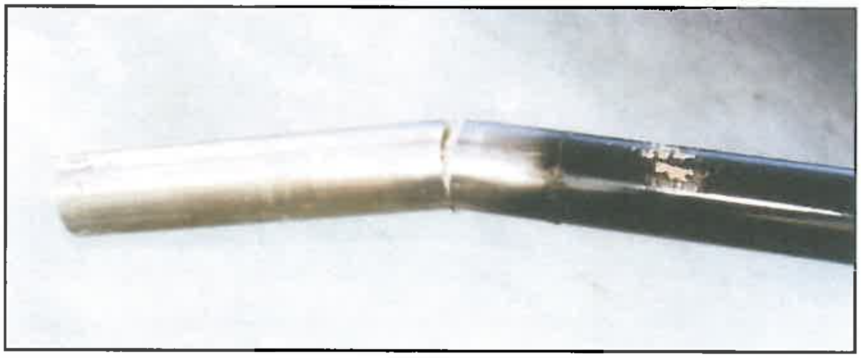

Photo 6d. Post-test Close-up Of The Exemplar Pole Containing The Reinforcing Bar In The Concrete.

3.3 Identification of probable point of failure.

Additional pole installations were inspected, and all displayed similar patterns of corrosion: either adjacent to, or up to a few inches above, the top surface of the concrete anchor.

Some installations were in irrigated lawns, at the soil level, sometimes with the stems of the grass above and even lying over the concrete anchor. Other installations in desert landscaping were flush with the soil, underneath the gravel cover. Desert landscaping is typically done with a gravel or rock layer on top of a heavy plastic film. Installation of the concrete anchor meant opening the plastic film, thereby providing an entrance route for water.

Installations inspected showed little or no drainage slope to the top surface of the concrete, and in some cases were uneven, indicating a lack of smoothing of the concrete during the installation. These and other factors increased the likelihood water would collect at the base of the pole, and potentially carry corrosive minerals to the pole.

Photo 7a. Corroded Pole Stub In Desert Landscaping

Photo 7b. Close-up Of Corroded Pole Stub In Desert Landscaping

Identification of probable mode of failure.

The basketball goal assembly has a natural vibration frequency, activated by a basketball striking the backboard. The resulting vibration is restrained at the point where the pole enters the concrete. The restraint is the nodal point of a resonant vibration wave and the free end of the system is at the mid-point of the wave. As a result of the restraint, the greatest stress is at that restraint point, producing multiple effects over time, including weakening the steel over time.

Another resulting effect of that stress is weakening of the powder coating on the pipe increasing the likelihood that water will contact bare metal and cause corrosion. The chemical result of corrosion is iron oxide (ferric oxide, Fe_2O_3) better known as rust. Because each molecule of rust contains three oxygen atoms, in addition to the two iron atoms, rust has a larger volume than the volume of the unreacted iron atoms. This increase in volume generates pressure, often resulting in the rust flaking off the unreacted surface. If the rust begins to develop underneath the powder coating, it will act to lift the coating from the surface, further exposing additional metal surface for more rusting. Once corrosion begins, the resonant vibration will accelerate the rate at which the rust falls off the pole, exposing new surfaces for additional corrosion.

A third effect is the fracturing of the concrete itself at and in the vicinity of the nodal point. The fractured concrete has no strength, and is unable to provide strength to the pole once failure begins.

3.4 Metallurgical testing

Elemental analysis[5] of a specimen from the subject pole agrees with the requirements for ASTM 1008 mild steel. Rockwell "B" hardness testing indicates a tensile strength of 68,000 psi which is within the expected range for this alloy. Alloys such as ASTM 1008 are not noted for corrosion resistance.

3.5 Discussion of coating on pipe, corrosion

Each pipe section is individually powder coated with a polyester resin at a nominal exterior thickness of 0.002 to 0.0025 inches. As a general statement, coatings made from polyester resins are not impermeable to water molecules, making it possible for rust to form underneath the coating. In addition, the coating is subject to scratching during normal handling and use, thereby exposing bare steel to environment.

Pencil hardness of the DuPont coating[9] is H to 2H, meaning the coating can be damaged by a pencil lead of that hardness. This is no harder than the leads in frequently used wood-cased pencils, which are usually 2H or 2½H.

The instructions for the subject pole included periodic inspections for rust. If rust is found, the instructions were to remove the rust and loose paint to bare metal by sanding and then repaint with a good metal primer, followed by two coats of black enamel. The existence of rust means that part of the tube has been consumed, reducing the strength of the tube. Merely removing the rust and repainting the tube does not replace the tube material, but will often mislead the consumer into believing the tube strength was still intact. Corrosion of the tube below the surface of the concrete base would be impossible to observe, and therefore would be impossible to repair.

3.6 Manufacturer's awareness of corrosion effects

Subsequent to the installation of the subject pole, but slightly more than four years prior to the fatal accident, the manufacturer revised the installation recommendations[10]. As part of those revisions, the manufacturer began furnishing a plastic sleeve to protect the portion of the pole embedded into the concrete anchor. The date of this recommendation was after injuries due to pole failures were being reported to the Consumer Product Safety Commission. This sleeve is referred to as an important safety feature, designed to inhibit rusting where the ground meets the pole. The date and overall wording of this announcement indicates that the manufacturer was aware at that time of the potential failure mode and the predominant failure location.

Effect of using reinforcing bar (rebar)

Poles containing only concrete, without a reinforcing bar inside, failed abruptly and totally when subjected to bending tests that simulated the collapse of a corroded pole. The basketball goal assembly is top-heavy and once the steel failed, the concrete could not resist the bending forces. This failure occurred when the pole was deflected only a few degrees from the vertical.

In contrast, poles containing a reinforcing bar in the concrete filling did not fail in a catastrophic manner. The steel of the tube broke, but the pieces above and below the break remained connected, even when the upper portion was bent 30 degrees from the vertical.

4 Conclusions

The powder coating on the pole did not prevent corrosion, resulting in loss of metal, progressively lowering the strength of the pole. Direct embedment of the pole in the concrete anchor may have also contributed to the corrosion.

The presence of the concrete inside the pole contributed to a false sense of safety and security. An exemplar pole filled with unreinforced concrete demonstrated abrupt total failure once the steel pole began to break when subjected to horizontal loads to the backboard because the concrete had no strength in bending or in tension.

Similar testing of an exemplar pole with the concrete containing a steel reinforcing bar clearly demonstrated the benefit of having the reinforcing bar: the metal pole was broken, the concrete was fractured, but the two portions of the pole remained connected to each other. The basketball goal assembly did not fall to the ground, even when the angle of bending clearly exceeded the angle required to cause failure in the exemplar pole without the reinforcing bar.

Thus, the testing done showed the basic design of the basketball goal system and its installation did not have the capability of failing in a "safe" mode, once the failure sequence began. The use of Failure Modes And Effects Analysis (FMEA), also called hazard analysis, would have identified the possible modes of failure, defined the corrective actions for reducing, or eliminating the modes of failure, and provided one or more recommended courses of action.

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