False Shear Cracking: An Early Sign of Alkali-Aggregate Reactivity

A distinctive crack pattern in the concrete of powerhouses and other structures subjected to constant shear forces may be one of the first indications of the presence of alkali-aggregate reactivity.

By James L. Gordon

About 15 years ago, I investigated a strange cracking pattern that had developed in a hydroelectric powerhouse containing a single, 62-MW vertical-axis Francis turbine. In describing the situation, the plant operator explained that the cracks in the concrete around the generator looked "as if a giant hand had grabbed the generator and twisted it clockwise a half degree."

Since that inspection, I have observed similar concrete cracking in two other powerhouses, each containing vertical-axis turbines. The sloping cracks appeared to be caused by shear forces, and, in fact, could have developed as a result of a structural design that neglected either upstream water pressure or the torque from the generator stator. However, a mathematical analysis of the shear forces present in each case indicated that they were well within concrete code limits, being no more than about 30 percent of the allowable stress.

Concrete cores from two of the three powerhouses were analyzed for alkali-aggregate reactivity (AAR), a condition in which concrete expands steadily over time. Laboratory tests of concrete from one powerhouse revealed no signs of alkali-aggregate reactivity. The test results from the other structure did not definitively indicate reactivity, but were in the "gray area," suggesting that some mild reactivity could be present. The head of the laboratory later remarked that, had he seen the second structure, he would have interpreted the test results as indicating very mild AAR.

These three cases, in which concrete showed signs of being subjected to excessive shear forces when such shear forces did not actually exist in the structure, led me to consider how the cracks might form as a result of alkali-aggregate reactivity. This article presents a basic hypothesis for the mechanism of crack formation and examines how conditions in each of the structures I observed could have produced this "false shear" cracking.

Jim Gordon, an independent engineering consultant, has 50 years of experience involving the civil and mechanical aspects of hydroelectric projects.

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Exploring the Basic Mechanism

When an element of concrete is subjected to a constant shear force, such as torque from a generator or water pressure, the principle stresses of tension and compression are at right angles to each other, and slope at 45 degrees to the shear force. These stresses by themselves do not lead to cracking or deformation in the concrete because they are considered during the structural design of the powerhouse.

If mild AAR is present, the concrete element is also exerting expansive forces in all directions and, being confined, is thus subject to compression. However, there are usually some directions in which the element is not confined, for example near a surface. In addition, depending upon the distribution of reactive aggregate gravel, moisture content, temperature, and alkali content in the concrete, there are areas of the concrete where the reactivity is lower than in other areas. Concrete elements in these areas will be subjected to tension from the expansion of the surrounding mass (Figure 1 on page 32).

Superimposing the shear stress and the stress due to expansion results in an increase in the tensile "shear stress" and a decrease in the compressive stress in the element having relatively low reactivity. The result is a crack that mimics the slope and direction of a crack caused by excessive shear.

Investigating Cracks at the Floor-Wall Contact

The first powerhouse where I observed "false shear" cracking contained one vertical-axis, 62-MW Francis unit with a 3.1-meter-diameter runner that was commissioned in 1956. For about the first 15 years of operation, no cracks had been observed, and repainting apparently had obscured any hairline cracks that had begun to form. But, by the time of my inspection in 1986, extensive cracking was evident around the periphery of the generator floor at the junction with the outside walls.

The slopes of the cracks were consistent with what would be expected from the clockwise torque forces emanating from the generator stator and being transmitted across the floor to the outside walls. The generator plinth would take some torque forces, but the much stiffer floor slab would resist most of the torque by transferring the torque forces in shear to the outside walls. Concrete

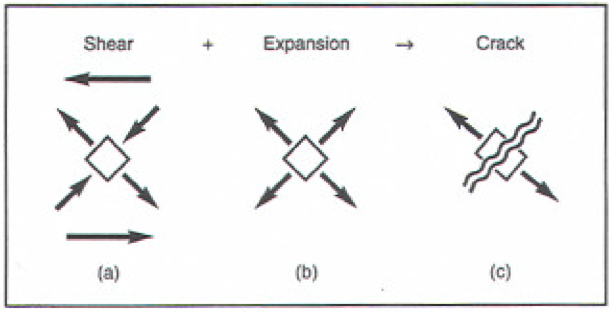


Figure 1: These diagrams illustrate how shear stresses on a concrete element caused by conditions such as generator torque or water pressure (a), combined with stresses developing from expansion due to alkali-aggregate reaction (b), could lead to cracking of the concrete in a manner normally associated with excessive structural shear stress (c).

cores were taken and submitted for alkali-aggregate reactivity testing, but the tests results were negative.

There had been no reported problems with unit alignment over the life of the project, although the powerhouse crane had derailed on a few occasions. These derailments later were proven to be related to expansion of the concrete floor, which caused the crane rails to separate slightly. In the years following my inspection, the unit continued to operate without serious alignment problems, despite the continued development of the cracks. The absence of alignment problems was due to the fact that, in this single-unit powerhouse, the concrete surrounding the generating unit was able to expand outward without affecting the alignment.

The question of the causes of the cracking remained unresolved until several years later, when the cracking became so extensive as to warrant further investigations. These investigations confirmed that alkali-aggregate reactivity was the cause of the condition.

A similar situation developed at a newer powerhouse constructed in 1983 and 1984 and commissioned in 1985. The powerhouse contains two 75-MW, vertical-axis Pelton turbines having runner diameters of about 3.2 meters. An inspection when the plant was 16 years old revealed fine hairline cracks in the generator floor and in the generator plinth. The largest cracks appeared at several locations around the floor-wall contact. The cracks could readily be explained by excessive shear stress—much to my own distress, as I was involved in the design of the plant. A recalculation of the shear stresses, however, showed that the stresses were well within code limits. As the cracks could not be attributed to excessive shear stresses, and as the pattern was similar to the one I had observed in the older one-unit powerhouse, I concluded that the cause was the combination of shear forces with mild alkali-aggregate activity.

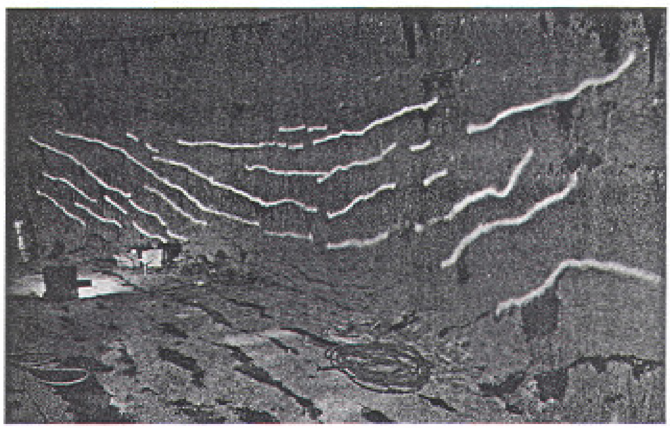
Expansion caused by alkali-aggregate reactivity is common among power plants in the region. These occurrences were recognized at the time of construction, and all aggregates were tested for potential reactivity. However, laboratory tests cannot detect very mild reactivity. It may be many years before the first sign of reactivity, in the form of false shear cracking, appears, and even longer before laboratory tests indicate the presence of reactivity.

Cracking in Draft Tubes and Other Structures

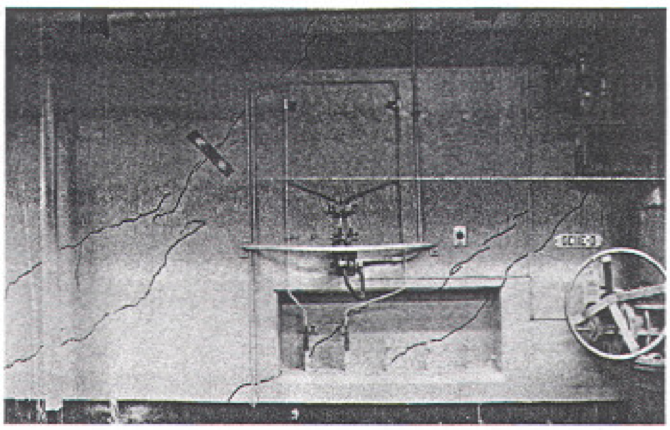
In 1989, I observed cracking in the concrete at a low-head hydroelectric station containing several large, vertical-axis propeller turbines with runner diameters of 6.4 meters. Each turbine-generator unit has an intake with three gates, a very short downward-sloping water passage, a concrete spiral casing, and an elbow-type draft tube.

When I inspected the powerhouse, the concrete had been in place for about 30 years. The operators reported that concrete movement had first been observed as elongation of the throat rings to an oval shape when the powerhouse was about 16 years old. Suspecting that the concrete movement was due to small differential movements in the foundation, the owner had initiated an extensive survey to detect such movements. However, the survey did not conclusively reveal any shifts of the foundation. Additional investigations also ruled out seasonal temperature changes as the cause of the concrete movement.

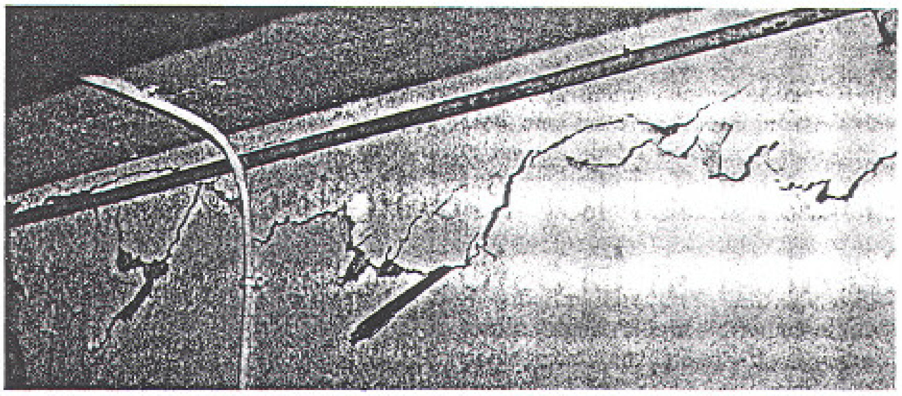
By 1989, extensive 45-degree shear cracks were evident in all transverse walls of the powerhouse, such as the intake and draft tube piers and generator casings. Of particular interest were the cracks in the concrete semi-spiral casing. These cracks sloped downstream on both sides and were flat in the middle of the downstream wall. The crack pattern was so symptomatic of excessive shear that we immediately recalculated the shear forces in the con-



The turbine semi-spiral casing wall in a low-head hydroelectric plant shows extensive "false shear" cracking. Cracks have been spray-painted white to facilitate recording them. Cracks on each side run at about 45 degrees, and the cracks in the center on the downstream wall are horizontal, as would occur when excessive shear stress is present.



In this photograph, taken with a wide-angle lens, the crack pattern on the concrete generator casing wall has been marked with a black pen. All of the cracks slope at 25 to 55 degrees. A glass slide crack monitor is shown on the top left crack.



A series of slanting cracks in the powerhouse wall just below the generator floor have joined together as the cracks opened. The dark object in the center of the photograph is a ballpoint pen, placed for scale.

crete of the powerhouse. The shear stresses in all of the cracked areas were found to be less than 30 pounds per square inch, which was well within the allowable stress.

Concrete cores were taken, and sent to a laboratory to be analyzed for alkali-aggregate reactivity. The laboratory report indicated that reactivity was not a likely contributor to the cracking, although the results were in the "gray area" where some reactivity might be present.

Even though such "false shear" cracking is not caused by excessive shear forces, the consequences still may be severe. At this low-head, multiple-unit powerhouse, extensive work was required to realign the units. As concrete expansion continued, a detailed investigation was conducted. Finally, the investigation revealed areas where the concrete was in compression, and the adjacent reinforcing was in tension, a situation that can only be due to alkali-aggregate reactivity. As the movement became more pronounced, the owner eventually cut slots in the concrete to accommodate the expansion.

Detecting, Responding to 'False Shear' Cracking

Based on my experiences, I arrived at the hypothesis that when there are shear forces combined with mild alkali-aggregate reactivity, a cracking pattern will develop that mimics the pattern produced by excessive shear stress. These "false shear" cracks can develop long before material tests or deformation measurements indicate the presence of reactive aggregate. When such cracks develop and a structural analysis indicates that the actual shear stresses are well within allowable limits, it is probable that alkali-aggregate reactivity is deforming the structure.

In a low-head powerhouse, false shear cracks typically appear first in the concrete walls of the generator casing parallel to the flow passage. These walls are subjected to large shear forces from the upstream water passage, but in many cases they are thin and designed only to support the upper floor and encase the generator—not to resist shear.

Fine 45-degree sloping hairline cracks usually will appear shortly after commissioning, and if they continue to open, a monitoring program should be implemented. If no further movement is detected after about one year, then the cracks are probably due to plain shear. When excessive shear is the cause of the cracks, the forces are distributed to the more rigid parts of the structure, and the generator casing cracks will not open further. However, if the cracks continue to open over a period of years, then early mild alkali-aggregate reactivity may be present.

It is not possible to stop the expansion of concrete due to alkali-aggregate reactivity. However, if early reactivity is suspected due to formation of "false shear" cracks, the plant owner can benefit from this early warning by monitoring the progression of the cracks, and comparing the rate of movement to the movement observed in other plants where reactivity has been detected. Such a program of monitoring can provide the owner with useful information about the severity of problems likely to develop in the future. ■

Mr. Gordon may be contacted at 102 St. John's Boulevard, Pointe Claire, Québec H9S 4Z1 Canada; Telephone and Fax: (514) 695-2884; E-mail: jimgordon@sympatico.ca.