INSTRUMENTS FOR MEASURING STRAIN AND STRESS IN CONCRETE

Dr. Roy W. Carlson was a legend in the field of concrete technology. His seminal work on mass concrete for large dams had a lasting impact in the field. He gave his lecture at the University of California, Berkeley on January 29, 1982.

My talk will be about the development of some types of instruments for measuring strain and stress, particularly those for embedment in concrete. I will confine my talk to meters which I have developed. After my talk, there will be time for questions and I will try to answer questions about my meters and about other instruments as well.

All of my instruments use unbonded elastic wires as the sensing elements. Although I received a rather basic patent for this kind of instrument, my interest was mainly in such devices as could be embedded in concrete. Other companies used my patent for other applications and did far more business than I did. My patent applied to all devices using the unbonded wires, so it was quite broad. It was prepared by my cousin Chester Carlson who invented Xerox and became rich. Chester had been graduated from Caltech in Physics; he had trained in patent law for 4 years in the Bell Laboratories and he attended law college for 4 years after that. So you can see that I had competent help with my few patents. Unfortunately the strain meter patent expired in 1953, some 29 years ago.

My interest in measurement of strain and stress began in 1926 when we were testing the Stevenson Creek Experimental Dam. This dam was built in the narrow and steep Stevenson Creek Canyon a few miles downstream from Shaver Dam and about 60 miles east of Fresno. The site was ideal for such a purpose because if the dam should fail, there would be almost no downstream damage. In fact, the 60-foot high dam had a reservoir less than 100 yards long. The dam was far thinner than would be allowed for a service dam, being only two feet thick at the crest and 7.5 feet thick at the base. The up-stream face was cylindrical and vertical, with a radius of 100 feet.

Every kind of applicable known at this time was to be made at the dam. Internal strains were to be measure for the first time in history. The strain method for embedment was conceived at the U.S. Bureau of Standards. The sensing element was a stack of carbon discs which would change in electrical resistance when compressed more or less. The assembled meter had a cylindrical steel body with end flanges 6 inches apart. One flange was connected to a rod which pressed against the carbon pile. The calibration was non-linear and fairly reproducible if the interior were kept dry. Lack of long-time stability and the need for low humidity were serious disadvantages.

When the test dam was loaded by filling the reservoir cracks appeared which were not expected if only water loading was acting. We decided that there must have been stresses due to other causes, mainly temperature change and these might be more important than the stresses due to water load. It as then that I decided to attempt the development of a device for measuring stress directly. It had become clear that a strain meter could measure only deformations, and these could be due a combination of causes of which stress might be a minor one.

Also, I thought that a better strain meter could be developed, one which could have long time stability and constant calibration. So I embarked on two lines of endeavor, first to design a better strain meter if possible and second, to design a device which would see only stress and be immune to any deformation which was not directly related to stress. I began at once to search for something which was stress sensitive. I knew that all soft metals exhibit large changes in electrical resistance under stress but their elastic limits are far too low to serve my purpose.

In 1927 some data in the Smithsonian Physical Tables caught my attention. The data reveal that when carbon steel wire is drawn down to very fine size, its tensile strength approaches the outstanding value of nearly a million psi! This means that it would stretch so much that even the mere change in length would cause a substantial change in electrical resistance. But I had learned that there is also an effect of stress in resistance, so I could hardly wait to discover how much the stress effect could be. What I found was that when the fine carbon steel wire was stretched by one per cent, the resistance increased by 3.6 per cent. This was not sensational, but it was good.

The development of the strain meter using unbonded carbon steel wire went trough large number of so-called improvements which I will not enumerate here. Good sensitivity was obtained because of three magnifying effects. First, the length of the elastic wire coil was made only about one-fifth of the gage length thus making a larger length change in the wires than in the gage as a whole. Second, the resistance change in the wire was 3.6 times the length change. Finally, by mounting two coils of the elastic wire such that one would increase in length while the other decreased, a double effect could be obtained.

A number of persons suggested using a wire composition which has no temperature coefficient of resistance. They seemed surprised when I said that I wanted a temperature coefficient so that my strain meter could serve both as a strain meter and as a thermometer. That was one fault with the meters used at Stevenson Creek; temperature had to be measured separately. In the present strain meter, the TOTAL resistance of the two coils is independent of deformation and can therefore be used to indicate temperature. The RATIO of the resistance of the two coils is independent of temperature and can therefore be used to indicate strain or deformation.

The strain meter which finally evolved for embedment in concrete was shaped like a one-inch diameter cylinder with a flange at either and for bonding to the concrete. The cover had a hollow section for flexibility and inside the cover were two steel rods connected to either end. The elastic wire coils were mounted on these rods such that when the end flanges were pulled apart, one coil increased in length while the other decreased. The space around the elastic wires was filled with oil to prevent corrosion. Some of the strain meters have been under observation at U.C. Berkeley for about 25 years without appreciable drift of the resistance ratios.

Besides the fact that nearly all engineers believed that stress could not be measured, the development of the stress meter met with all manner of obstacles. An early set back came in 1928 when the stress meter was merely an idea of something which might be made. I had mentioned the concept of the stress meter to the Pacific Coast Editor of the Engineering News Record (ENR) who was a good friend. He begged me to prepare an article about it for publication. The article was written and submitted, but it was also submitted to a famous consulting engineer (Fred Noetzli) for a review. The reviewer condemned the article saying " Don't ever publish that because the subject matter is unsound". The article was never published. This was before a single stress meter had been made and before there was even a design for one.

The engineer who condemned the article happened to be a consultant on several dams for which I was the test engineer. This gave me the opportunity to discuss my ideas with him from time to time. For two years he stubbornly refused to accept the idea of the stress meter and kept repeating that only strain could be measured. Then one day in his office in downtown Los Angeles, he suddenly realized how the meter functioned and he became so excited that he missed his lunch. He then sent a letter of apology to ENR saying that Carlson's stress meter was based on sound principles.

At last I realized how much at fault I had been in not explaining the auction of the stress meter so an engineer could understand it. It seemed to me that engineers and physicists must think differently, because I had encountered no difficulty with physicists. At any rate, I decided to explain the stress meter in a different way as follows: Let's consider the difference between the measurement of strain (deformation) and that of stress (force). An instrument to measure deformation should be in a shape of a rod. If one imagines a thin rod embedded in a material like concrete, the rod will deform lengthwise very nearly the same as the surrounding material. Now if the rod is made thinner and thinner until its diameter approaches zero, it will have to change in length exactly like the surrounding material. The only requirements is that the rod have a finite modulus of elasticity. The strain meter therefore is shaped like a rod and while not infinitely thin, it is thin enough to make the error due to lack of thinness only a few per cent.

An instrument for measuring stress, on the other hand, should be in the shape of a thin plate. Consider such a plate with a finite modulus of elasticity and embedded in a continuous material. If this plate were to be reduced in thickness until it approaches infinite thinness, the stress through the plate would approach exactly the same stress as that in the surrounding material. Therefore, to make a stress meter, one should make a device in the shape of a thin plate and provide some means of measuring the stress in the plate. Many schemes were considered and tried for doing this.

The most practicable scheme seemed to comprise a diaphragm made up of two steel plates with a fluid film between them. For the measurement there would be a small strain meter which could measure the deflection of a smaller, internal diaphragm actuated by pressure in the fluid film. The deflection of the internal diaphragm would be proportional to the stress. This was essentially the stress meter which finally evolved.

He fluid for filling the space between the two plates which comprised the main diaphragm was a problem. Neither oil nor water were acceptable, both their thermal expansions and their compressibilities were far too great. The best liquid seemed to be mercury, although it leaves much to be desired. Its compressibility is favorably low but its thermal expansion is a problem. Since the mercury is confined laterally between the two plates, its thermal expansion in the critical direction becomes almost three times the linear expansion when unconfined. What this means is that the tendency of the mercury to expand in the direction tending to spread the plates apart becomes 13 times that of steel. The only solution here seemed to be to make the mercury film as thin as practicable, and this turned out to be about 0.007 inch.

The compressibility of the stress meter diaphragm was a problem. It was obvious from the start that if the meter were much more compressible than the surrounding concrete, it could not possible be subjected to the same compressive stress. Therefore, in 1935 I made a finite element analysis without benefit of computer to see how much difference in

compressibility could be tolerated. With the shape of the diaphragm I had adopted, I found that if the meter were twice as compressible as the surrounding concrete, it would be subjected to 7 per cent less stress than the concrete. On the other hand, if the meter had zero compressibility, it would register 7 per cent more than the concrete stress. Thus, it was concluded that the compressibility must be no more than double that of the concrete and preferably less. This was accomplished by (1) polishing the interior surface of the diaphragm so there was no roughness for the mercury to squeeze into, (2) developing a vacuum filling technique for the mercury to eliminate all air, and (3) keeping the internal diaphragm so that its deflection would not contribute seriously to compressibility.

Another problem was the sensing element. There seemed to be no easy way to make the strain meter unit small enough to hidden inside the diaphragm. Therefore, it was allowed to extend out from the middle of the main diaphragm, but isolated from the concrete by means of porous, fabric cover. This worked well in most cases but if the meter happened to be oriented at an angle with the principle stress, the eccentric pressure of the concrete might tilt ever so slightly and cause an error. The least reading of the strain-meter unit was approximately 0.00002 inch so even a slight tilt would extend the meter more than this and thus indicate tension. This problem was corrected in 1978 by having a protective tube around each strain unit so that the concrete could not touch even the fabric cover.

I spoke earlier of setbacks. One of the worst was when the Bureau of Reclamation in Denver decided to test the stress meter. They cast a larger cylinder, 3 feet in diameter by 6 feet high and embedded three stress meters in the concrete as it was cast. When the cylinder was half full they placed the meters, without waiting for bleeding to stop. As the aggregate particles tended to settle, water rose toward the surface and collected under each stress meter. The resulting void under each meter prevented the intimate contact between meter and concrete which is essential for proper functioning. The net result was that when the cylinder was loaded, the stress meters showed far less than the applied stress and the meters got a black mark.

Another setback was in India where stress meters were used in the Koyna Dam. The installation was faulty again and the meters gave erroneous indications. The main trouble here was with meters to measure stress in directions other than principle ones. The concrete pressed against one side of the strain-meter nit, tilting it slightly so that it was extended and thus showed tension. Although some of the meters gave reasonable results with others showing tension, there could be no confidence in any of the results. A change in the meter design was made then to prevent this kind of behavior happening again. There is now a protective steel tube around the strain meter unit so that the concrete can not touch it.

Although there were more setbacks, there were also some very useful results obtained with strain meters. A good example is the Dworshak Dam in Idaho. This dam is the largest ever built by the Army Engineers and is over 700 feet tall. Nearly 100 stress meters were embedded in 3-meter clusters in one of the highest monoliths of the dam. Hundreds of strain meters also were installed. The stress meters gave the principal stresses in a plane perpendicular to the axis with almost no analysis required. Although the dam was completed in 1972, the strain meter data have not yet been studied enough for obtaining the stress meters demonstrated their superiority. The stress meters now provide a quick way of checking for any possible change in stress distribution, which would be more difficult with the strain meters.