100th Anniversary of the Monitoring of Stevenson Creek Experimental Dam: Reflections on the Past and Future Advancements on Strain Sensing and Strain-Based Monitoring of Civil Structure

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ABSTRACT

Stevenson Creek Experimental Dam was bult near Fresno, California, in 1924-1925, with the aim of studying the structural behavior of arch concrete dams. To achieve the project objectives, six types of sensors were deployed: four types of sensors were based on mechanical devices that were operated manually, but two novel types of sensors, deflection (relative displacement) sensors and embeddable strain sensors (consisting of a stack of carbon discs), were both based on electrical resistance and were assessed remotely, via wires. While the use of mechanical manual sensor technologies in real-life applications can be traced back to the 19th century, what makes the application of novel sensors in Stevenson Creek Experimental Dam paradigm changing, is the fact that the readings of resistive deflection (relative displacement) and strain sensors were performed from a remote room. The centenary of this technological achievement, which represents the first application of modern monitoring technique in the United States of America (to the author's best knowledge), stimulates reflection on the past accomplishments and the future advancements on strain sensing and strain-based monitoring of civil structures. Hence, the aim of this paper is to summarize the progress in strain sensing technologies and their impact on strain-based monitoring over the first hundred years, and to give a few glimpses about directions of future developments.

STEVENSON CREEK EXPERIMENTAL DAM

Stevenson Creek Experimental Dam was designed by Dr. Fred A. Noetzli (1887-1933) [1], Swiss American engineer, who was a pioneer in thin arch and multiple arch dams. As its name suggests, the purpose of the dam was to perform full-scale experiments that would help understand design, construction, and structural behavior of these innovative structures [2]. The main interested parties in these tests were Engineering Foundation and Southern California Edison Company, the former as the engineering society and the latter as the industry involved in the booming electrification of the United States of America.

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Given its experimental nature, the dam was built in a "small gorge of such a shape as to give a very small reservoir capacity" [2], as schematically shown in Figure 1 [3]. The gorge and is located approximately 60 miles (97 km) east of Fresno, California, on Stevenson Creek, a tributary of the San Joaquin River. As the figure shows, a large conduit of the Southern California Edison Company's hydroelectric system was guided there, so the water from that conduit could be used to fill the dam and perform the tests.

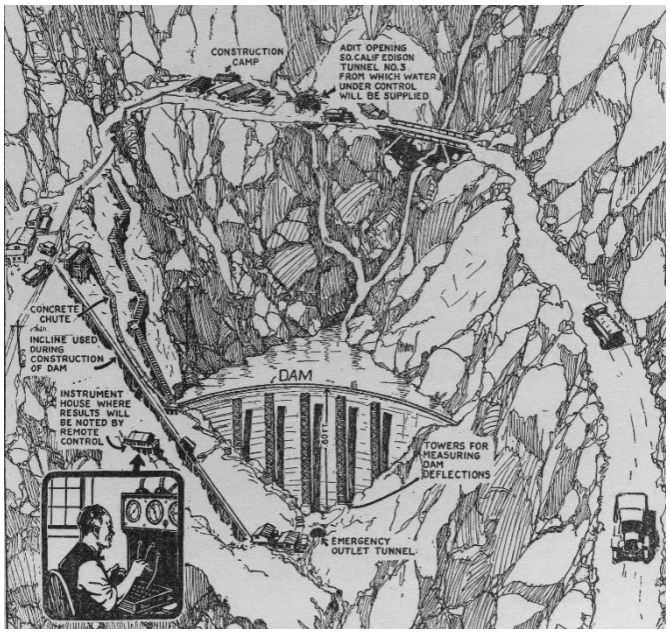

Figure 1. Schematic of the implementation of a monitoring system in Stevenson Creek Dam (image: The Stevenson Creek test dam (1925). Southern California Edison Collection of Photographs (photCL SCE), The Huntington Library, https://go.exlibris.link/461Zn0Q0, accessed on 02/28/22), modified from [3].

The dam was ~60-ft tall (~18.3-m) with constant horizontal radius of curvature of 100 ft (30.5 m) and vertical upstream face. The thickness of the dam was invariable in the top half and equal to 2 ft (0.6 m), while in the lower half it increased from 2 ft to 7.5 feet (2.3 m). Cross-section at the deepest point of the dam is shown in Figure 2 [4].

Figure 1 shows two important facts: (1) the dam was monitored for deflections, and (2) some data was collected and accessed remotely, via electrical wires, from for-the-purpose-built "instrument house". In fact, the dam was monitored using large number of sensors, some of them existing and modified for the purpose of field experiment, but some of them novel, invented for the purpose of the experiment. Instrumentation plan is shown in Figure 2 [5]. The following sensors were used [2]: (1) **Strain gage** – a variation of the mechanical Berry strain gauge, modified by Col. George S. Binkley; (2) **Radius meter** – mechanical instrument designed to measure change in radius of curvature of the dam, based on Ames (dial) gauge; (3) **Clinometer** – mechanical instrument designed to measure deflection based on Sterrett gauge (micrometer); (4) **Level bar** –instrument similar to clinometer designed to determine the change in inclination of the lower portions of the dam and of the foundation rook; (5) **Electric telemeter** – a novel embeddable strain and temperature sensor consisting of a stack of carbon discs, developed by Barton McCullom and O. S. Peters of the Bureau of Standards, today's National Institute of Standards and Technology – NIST [6]; and (6) **Resistance micrometer** – novel sensor designed to measure deflections by measuring

change in distance between the dam and for-the-purpose-built steel towers (see Figure 1) but actually used to monitor underwater crack opening [2].

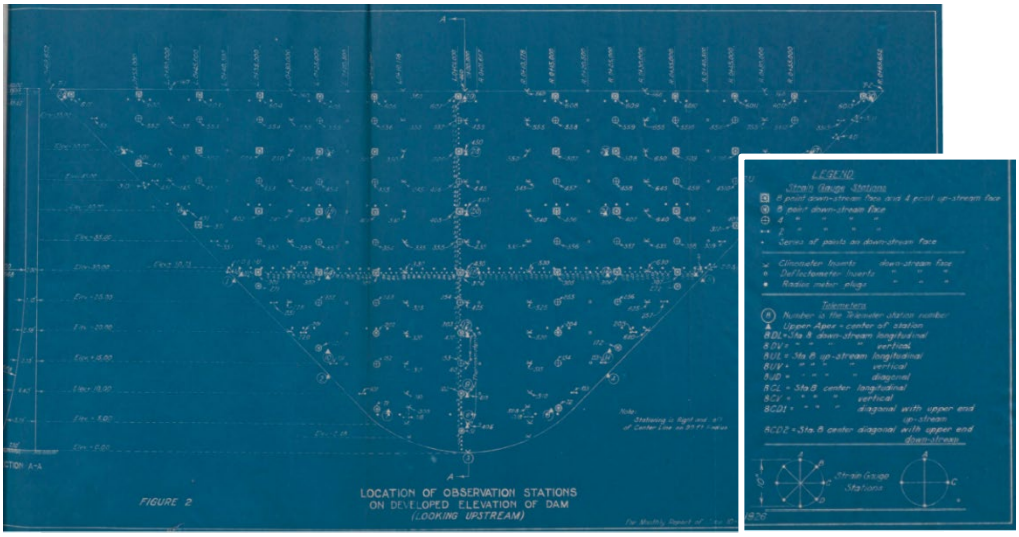

Figure 2. Original sketch of instrumentation plan taken from [5]; dam cross-section is shown to the left.

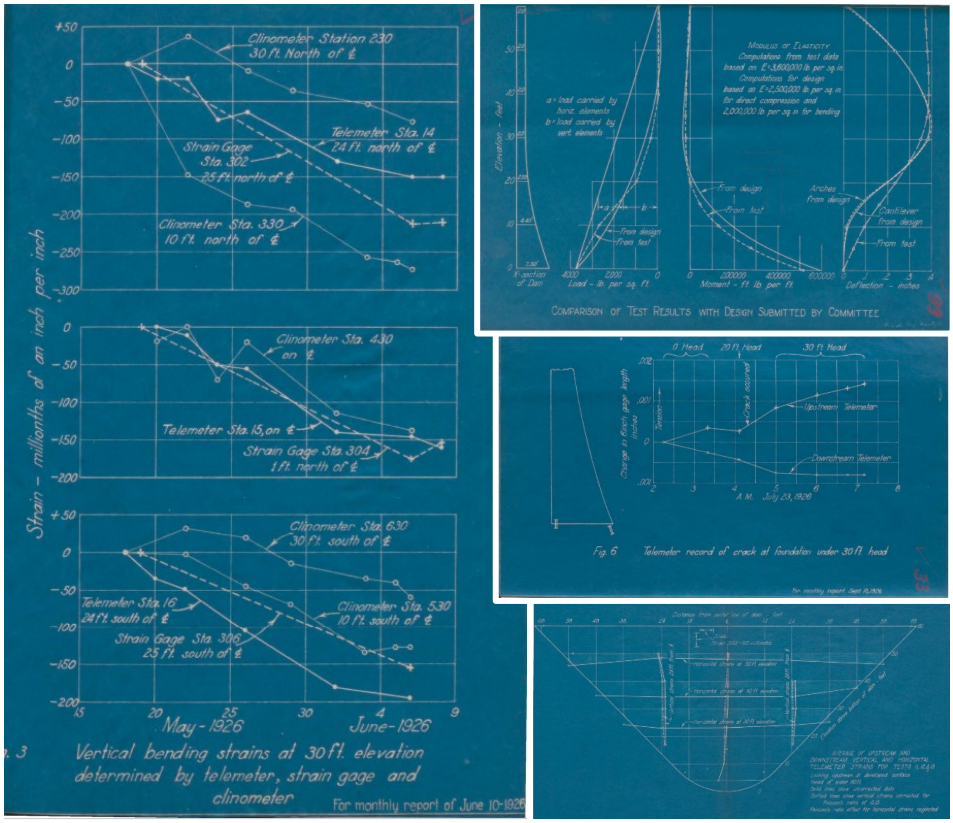

Figure 3. Example of original presentation of results of measurements taken by telemeter – embedded strain sensor – and associated data analysis (taken from [5]).

While the use of mechanical manual sensor technologies in real-life applications can be traced back to the 19th century (e.g., [4]), what makes the application of novel resistive sensors in Stevenson Creek Experimental Dam paradigm changing, is the fact that their readings were performed from a remote room. To the best of the author's knowledge, this technological achievement represents the first application of modern

monitoring technique in the United States of America (USA), and probably the world. If that statement is correct, then the results of monitoring represent many other firsts: the first long-term strain monitoring results, the first strain distribution map, the first deflection map calculated from strain, the first crack detection in real-life settings, the first system identification, the first application of embedded sensors, etc. Few examples of these results are shown in Figure 3 [5].

Figures 2 and 3 demonstrate that levels of sophistication of the monitoring system and the data analysis were both extremely advanced and comprehensive; they have all components of modern, 21st century, monitoring applications. The cost of the entire experiment was estimated to $120,000, which includes construction of the dam, instrumentation, carrying out the test, data analysis and reporting [7]. This is approximately equivalent to $2.26 million [8]. In addition, there was a lot of voluntary work performed by many individuals and institutions involved. The 100th anniversary of this very sophisticated technological achievement, stimulates reflection on past accomplishments and the future advancements on strain sensing and strain-based Structural Health Monitoring (SHM) of civil structures.

DEVELOPMENTS OF STRAIN-BASED MONITORING

First Generation of Strain Sensors - Discrete Electrical Strain Sensors

The first ideas related to strain sensors (to the best of the author's knowledge) date back to Lord Kelvin's demonstration to the Royal Society of London in 1856, that the electrical resistance changes in a metallic conductor when the latter is exposed to mechanical strain [9]. 82 years later, in 1938, Edward E. Simmons and Arthur C. Ruge, invented what is today known as strain gage [9]. However, the first practical strain sensor was invented 19 years earlier, by German researcher Otto Schaefer (in 1919) [10]. His sensor was based on the principle of a vibrating wire (VW). Soviet professor, N. Davidenkoff, learned about that invention in 1926, and he re-invented the VW sensor (he named it "teletensometer"), made it embeddable in concrete, and deployed it in the Zoragetstroi Tunnel in 1931 [11]. In parallel, André Coyne patented his own type of the VW sensor in 1931 (he named it "témoin sonore"—sonic witness/sensor) and implemented it in a dam on the La Bromme River [12]. In addition, he founded the company Télémac, which still exists. While electrical telemeters, used in Stevenson Creek Experimental Dam, represent the first large-scale implementation of strain sensors in real-life settings, they suffered from long-time instability. Roy Carlson improved the sensor in the 1930′s (he named his sensor a "strain meter") [13] and deployed it in Hoover Dam; the sensor is today known as Carlson Strain Meter. Thus, 1920's and 1930's witnessed the birth of modern strain-based monitoring of civil structures and yielded the first generation of strain sensors.

Second Generation of Strain Sensors - Fiber-Optic Strain Sensors

The second revolution which yielded the second generation of strain sensors, i.e., Fiber-Optic Strain Sensors (FOSS). Initial research on FOSS started in [e.g., 14-15], the first applications appeared in 1980's, and commercialization followed in 1990's [3]. While the Fiber Bragg-Grating (FBG) sensors are probably the best known from that

generation, there are several other physical principles behind the FOSS, discovered by great scientists from the late 19th and early 20th century: Albert A. Michelson, Lawrence and William Henry Bragg, Ludwig Mach and Ludwig Zehnder, Charles Fabry and Alfred Perot, Rayleigh (John William Strutt), Léon Brillouin, and Chandrasekhara Venkata Raman (and several of them are Nobel Prize recipients). Two distinguished groups of FOSS were developed discrete (point) sensors and truly distributed sensors [3]. The former are based on Extrinsic Fabry-Perot Interferometry (EFPI), Michelson and Mach-Zehnder Interferometry (so called SOFO sensors), Fiber Bragg-Grating spectrometry (FBG), or intensity losses; the latter are based on Brillouin scattering or Rayleigh scattering [16].

The development of FOSS resulted in two paradigm changes. The first paradigm change was the availability of long-gauge sensors, as they improved accuracy in strain measurements (especially in inhomogeneous materials such as concrete), improved damage detection capabilities of strain sensors (by larger spatial coverage), and made possible monitoring at a global structural scale (as they provided spatial coverage that can instrument entire structure) [17]. These sensors enabled the first widespread SHM applications (with 100+ sensors) at a global structural scale in the 1990′s (e.g., [18]).

The second paradigm change was the availability of truly distributed sensors. These sensors have a form of a cable sensitive to strain at every point along its length. Hence, distributed FOSS enabled monitoring of a 1D strain field along the entire length of sensors. Thanks to their very large spatial coverage, distributed FOSS enabled direct damage detection and enabled integrity monitoring of the structure [17]. Distributed FOSS were first experimented for temperature sensing in the 1980′s (e.g., [19]), and soon after for strain sensing (e.g., [20]). A true disruption was made in the 1990′s, when the distributed FOSS based on Brillouin and Rayleigh scattering were developed (e.g., [21] and [22]). They became commercially available at the turn of 21th century.

Third Generation of Strain Sensors - Two-Dimensional (2D) Strain Sensors

Strain sensors from the first two generations provided excellent means for evaluating stresses and deflections (indirectly from strain) as the indicators of structural safety and performance. Nevertheless, damage identification, while successfully performed in many specific cases, remains generally challenging, as the damage occurring at the locations distant from sensors may pass undetected. The most reliable way of identifying the damage is through direct sensing, i.e., by having a pervasive presence of sensors in the structure, so that any damage that occurs will be in contact with some sensors, and thus it will be identified reliably. This motivated a new wave of research at the turn of the 21st century resulting in the third generation of strain sensors.

While the first two generations of strain sensors were technology-driven and motivated by an achievement of high measurement performance, the third generation of strain sensors was mostly aimed at sensors that can cover large 2D areas of structures, i.e., enabling direct sensing, where the aim is not to measure strain accurately, but the strain is rather used a damage indicator. The paradigm shift that the third generation of sensors offered is in focus on large spatial coverage enabling direct damage detection at the expense of accuracy in strain measurement. This shift is justified because the first- and the second-generation sensors already provide highly accurate strain measurements.

Two subdivisions of third-generation sensors were identified: contact-based and non-contact-based sensors. The research on contact-based sensors resulted in various

prototypes of 2D quasi-distributed sensors such as expandable sensor networks (e.g., [23]) and sensing sheets (e.g., [24]), and truly distributed sensors, such as sensing skins (e.g., [25-27]), photonic crystals (e.g., [28]), nano-paints (e.g., [29]), and more.

The non-contact-based strain sensors generally involve digital image processing approaches. Research on these sensors flourished in the second decade of this century, boosted by the progress in computer engineering and information technologies. Digital image processing is typically used to map displacements of points (pixels) on structure surface (image); then, the displacement map can be used to determine the strain field (e.g., [30]) or to identify damage such as spalling or cracking (e.g., [31]).

The paradigm-shifting promise of the third-generation sensors is their potential to reliably identify damage over 2D structural surfaces by direct sensing, which, in turn, has promises to enable 2D integrity monitoring at a large scale.

CONCLUSIONS AND FUTURE PERSPECTIVES

Strain sensors have a century long history in Structural Health Monitoring (SHM) of civil structures, as summarized in Figure 4 [3].

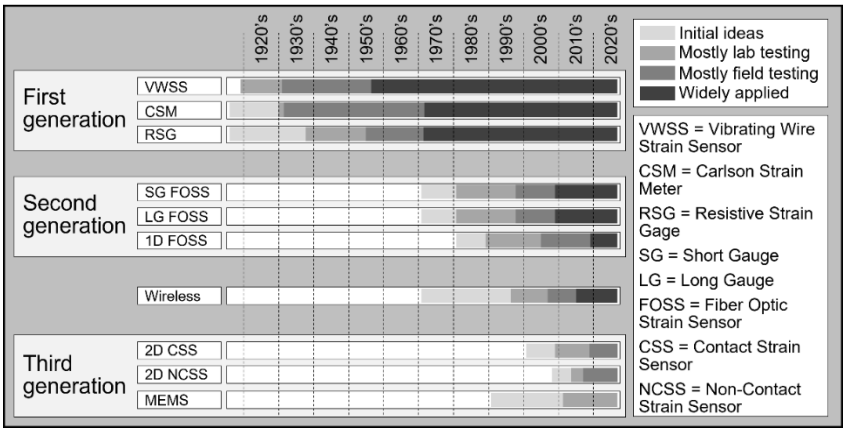

Figure 4. The first century of research and development of strain sensors (modified from the slides of author's university course CEE 537 Structural Health Monitoring) [3].

This century-long journey resulted in three generations of sensors that created and significantly expanded the capabilities of strain-based SHM, as shown in Figure 5. Short-gage sensors enabled monitoring at local scale, long-gauge at structural scale while distributed sensors enabled integrity monitoring [17]. This prolific progress in strain-based SHM was only possible though a convergent research that involved other branches of engineering and science, such as electrical and computer engineering, informatics technologies, mathematics, and computer science.

Current and future research and development in strain sensing have various perspectives. One important perspective is completion of research and development regarding the improvements and enhancement of performance of sensors of the first three generation of strain sensors, including their extending longevity and long-term reliability. Another important perspective, not directly related to sensor development yet crucial for its use, is in getting full benefits of data collected by strain sensors and their use in the prediction of future structural behaviors, using advanced artificial intelligence and machine learning approaches (e.g., [32]). Future research could expand

from 2D to 3D distributed and quasi-distributed strain sensing so that the entire volumes of structures or structural components can be instrumented (e.g., [33]). Another perspective is in exploration of digital approaches, such as virtual and augmented reality, enabling human-structure interactions in strain measurement (e.g., [34]).

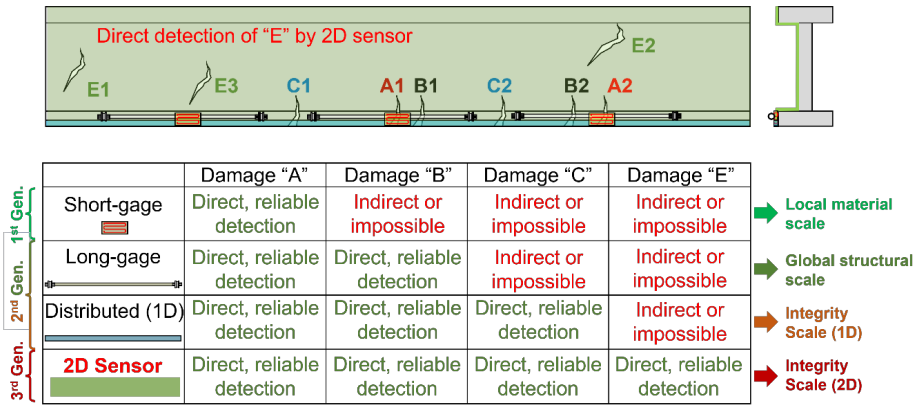

Figure 5. Progress in strain sensors damage detection capabilities and their transformative impact on the scale of applicability in SHM (modified author's university course CEE 537 SHM) [3].

In conclusion, one century of research, development, and applications of strain sensors and strain-based SHM is truly remarkable. Strain-based SHM enabled better understanding, optimized maintenance, and improved safety of infrastructure worldwide. It boosted the economy by creating many companies and an entire industry sector. And despite its century-long tradition, strain sensors and strain-based SHM continue to be vibrant areas of research and innovation.

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