is not well implemented in many places. If one accepts results that are not as precise as today's risk-averse society demands, and if the choices of construction materials, configurations, and systems are limited to those that were best understood, then the early engineering state of the art does not look so primitive. Implemented by the best of the early seismic designers, the state of the art was conservative and solved many practical problems, though the engineering was approximate. It was able to produce safe construction but without the economy that is also a goal of engineering. It still can teach us some basic seismic design principles, even if we use a "sharper pencil" today to achieve more efficient results. They say you cannot put a square peg in a round hole, but you can—if you make the hole big enough.

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7

1940–1960

Major Advances in Understanding and Design

The broad social and historical context in which the earthquake engineering field developed in this era included the war that even more than World War I deserved the term "World" in its name. World War II, ranked the way earthquakes often are in terms of fatalities, is at the top of the list of military conflicts, accounting for more than 60 million deaths. At its conclusion, the use of two atomic bombs against Japan by the United States inaugurated the Atomic Age. After the war, decolonization spread rapidly. India and Pakistan gained independence in 1947. Most of Africa's European colonies achieved independence after 1960, though by that year Nigeria and the Republic of the Congo were already states, and all of Mediterranean northern Africa except Algeria had turned into independent nations. Like the dissolution of the Ottoman, Russian, and Austro-Hungarian empires after World War I, the newly created states rarely achieved political stability, wars among them were frequent, and only a minority achieved rapid economic growth.

"Technology" is a term used today to refer to computer technology, but in this era of the 1940s and 1950s it referred to what was created by the fields of aeronautical, mechanical, electrical, and civil engineering, not computer science or electronic engineering. Computers in that era had yet to have a pervasive effect on the world, and by 1960 they had only a small effect on earthquake engineering, hence the story of their great impact on the field is reserved for the next chapter.

The Soviet Union put an earthly object into orbit in 1957, by which time jets rather than propeller-driven airplanes were in ordinary use carrying passengers across continents and oceans. Although television had been invented earlier, in this era it became practical and common in industrialized or developed nations. Both the Salk and Sabin vaccines to prevent poliomyelitis were developed, medical breakthroughs that spurred the development of similar developments continuing to this day, in which a new vaccine is developed, sometimes to combat a newly developed strain of infectious bacteria or virus, and mass immunizations are quickly carried out.

In this era, the field of earthquake engineering took on a vocabulary of concepts and terms, a set of research and practice methods, and a knowledge base that proved to be sufficient to boost the field to where it would be at the end of the twentieth century. With few exceptions, developments that follow this era can be traced to predecessors that will be surveyed in this chapter. According to Thomas Kuhn's book, *The Structure of Scientific Revolutions* (1962), the history of science can be approached as a hunt for major revolutions, while regarding the mundane, incremental science accomplished in between revolutions to be merely "normal science," an accretion of old ideas—paradigms, to use Kuhn's term, which has since become a cliché. Although Kuhn's theory has been influential, it does not explain the history of earthquake engineering over the past 150 years. There is great continuity in the thinking of Mallet, Milne, Koto, Danusso, Sano, Naito, and others, down to the present day. There have been major refinements and corrections of error through the twentieth century, but "revolution" is too strong a term to use for any of its stages.

In the 1800s, the first earthquake engineering researchers knew that dynamic response of structures was central to understanding earthquake damage, and as more data were accumulated, generations that followed came up with more accurate findings. But that was not a fundamental change in the mind-set, merely the accretion of more knowledge to apply dynamics more thoroughly. Earthquake engineering did not come to an intersection and make a left turn at some point in the twentieth century; it proceeded ahead on the same road. With more funding for research and education, more instruments to provide quantitative data, and more calculating machines (computers), that road became a highway, but it proceeded on the same azimuth. If this were a history of earth science, the term *revolution* would be quite appropriate; the rise of plate tectonic theory is enough evidence to prove that point, as is later discussed. To use the term of eighteenth-century geologist James Hutton and nineteenth-century geologist Charles Lyell, engineering is essentially a field that develops via gradualism.

In the 1900–1940 period, seismic regulations in building codes or industrial standards were rare; by the 1940–1960 period, they were relatively common. Further changes in codes occurred as revisions to editions of previous codes, not in the form of completely rewritten codes, for two reasons. First, as just noted, the underlying knowledge base was incrementally increased, and second, engineering is not science. Engineering must get things built. Civil engineers design the big things of our environment we live in and around everyday, and it is not feasible to suddenly change construction patterns.

The leading engineers in this period knew that inelastic behavior was central to the field but needed more testing, analysis, and observations of actual earthquake damage to develop that branch of the field into practical design methods. One of the papers at the first World Conference (Rosenblueth 1956) dealt with "Some Aspects of Probability Theory in Aseismic Design," a subject much evolved since then but not a completely new subject in the field. And the study of the third basic theme of earthquake engineering, dynamics, matured in this period sufficiently so that when computers arrived in the next era (1960–2000), structural dynamic theory could be rapidly applied.

To return to the analogy with aviation used in the previous chapter, in this era airplanes evolved from earlier precedents and proved themselves to be eminently practical. Using airplanes to carry passengers for a profit was rare before 1940, but common afterward (after World War II ended). Vast tracts of land were devoted solely to tending to the needs of the planes, passengers, and cargo—that is, airports became ubiquitous parts of the landscape. Jet airliners were flying across oceans at speeds and altitudes that were still comparable to the latest model jet passenger planes in use at the end of the twentieth century. Likewise, the field of earthquake engineering as of the beginning of the 1960s reached a practical, established level and became recognizably the same field it is today, only then it was much smaller. That the field could have developed to such a degree before the 1960s with such a small number of people in it is testament to the fact that it was able to attract the best and brightest in the civil engineering field to its challenges.

When one considers a representative list of the most influential engineers in the earthquake engineering field who took up the discipline no later than the 1950s, an interesting generalization can be derived. The following list is not exhaustive, but illustrative of the point about to be made: Liu Huixian and Hu Yuxian in China; Riki Sano and Tachu Naito in Japan; George Housner, Nathan Newmark, John Blume, Joseph Penzien, Ray Clough, and Vitelmo Bertero in the United States; Arturo Danusso and Modesto Panetti in Italy; S. L. Kumar and Jai Krishna in India; Robert Mallet and John Milne, from the United Kingdom. They did research on a number of earthquake engineering topics, not just one. Although all of them were civil engineers, they all spent a great deal of time dealing with the seismological side to the earthquake problem. Today, specialization is the rule, and it is difficult to name someone who joined the field from the 1980s onward who is known as an expert in both the engineering and seismology aspects of the subject. C. Allin Cornell (1938–2007), in his 1988 Seismological Society of America presidential address, observed:

> I shall be the last engineer to be President of the SSA. Personally, I hope the future will prove me wrong, but I see at least the following three forces at work reducing the active involvement of engineers in the Society. First, in the last decade, strong motion recording and prediction (both empirically and theoretically) have become interesting to seismologists and geophysicists, gradually relieving engineers of that responsibility.… Secondly, the evolution of the engineering practice away from "worst case" design criteria and the now widespread use by professional earth science firms of probabilistic seismic hazard analysis (with its resulting continuous spectrum of ground motion levels and probabilities) eliminate the previously critical need for engineers to get involved "up front" in the seismic input characterization for a project.… Thirdly, and perhaps most significantly, in the last twenty years rapid growth in funding and interest in earthquake engineering research has led to many organizations, conferences, and journals that provide engineers a more specialized forum. (Cornell 1988, p. 1020)

When earthquake engineering was young, there were so few in the field that specialization was not possible. When the Earthquake Engineering Research Institute (EERI) in the United States had its first meeting in 1949, there were only 14 members to invite to meetings, and for years the slowly growing membership of that organization met as a group in one room, whereas today organizations in the field function with numerous committees and subcommittees on various topics. Conferences have simultaneous sessions, meetings in separate rooms, broken down finely into topical and disciplinary areas. The structural designer confronting earthquakes takes the pieces of the puzzle contributed by others—the architect, the seismologist, the geotechnical engineer—and must put them together. In the early days, those other pieces were not delivered as tidy packages but as unsorted fragments. The engineer's tasks could not be subdivided and handed off to others. Today hundreds of employees in a government agency typically do research to develop seismicity or geologic hazards maps for design purposes, but that was not always so. Structural engineers had to try to extract useful strong-motion information from seismology in the early years, whereas today an entire geotechnical engineering profession exists that takes on that role. An engineer did not specialize in either steel or concrete design in the early days, whereas in today's design office, it is common for structures of one material, such as steel, to be assigned to one engineer specializing in it and projects using another, such as concrete, to be tasked to another engineer. Rather than being a handicap, the role of generalist that was forced upon the early leaders in the field, leaders discussed in this chapter and earlier ones, gave them a tremendous advantage—they thought about the entirety of the earthquake problem. And when one thinks from first principles about the entirety of a problem, some innovative accomplishments are possible. The era somewhat arbitrarily defined here as 1940–1960, or extending a bit further, is the last in which the leading earthquake engineers were generalist experts in the entire field.

Laboratory and Field Instrumentation

Stephen Timoshenko (1878–1972) notes how the railway industry brought about early structural testing in the laboratory and in field applications in the mid-1800s, such as the collaboration of the design engineer Robert Stephenson (1803–1859), testing engineer William Fairbairn (1789–1874), and mathematician Eaton Hodgkinson (1789–1861) in the design of the Britannia Bridge, which began in 1845. Timoshenko notes (1953, p. 276) that "the introduction of iron and steel into structural and mechanical engineering made experimental study of the mechanical properties of those materials essential." As the nineteenth century began, the two leading engineering countries, France and Britain, took differing courses, the former specializing in mathematical theory about structures and materials and the latter conducting tests of structural specimens as they were about to be designed into Industrial Revolution construction. Both analysis and testing were to be essential in earthquake engineering, and both continue today.

In the 1940–1960 era, several important inventions of instruments occurred that served earthquake engineers well in the laboratory, which are discussed in more detail in Filiatrault (2003) and Reitherman (2003b).

Perhaps the key invention of the 1930s in engineering as a whole, not limited to our small specialty area of earthquake engineering, was the electric resistance strain gauge. Stress can easily be calculated, distributing out a force through the material that resists it, but stress is usually only indirectly measured by relating it to strain. Early strain gauges were mechanical, carefully calibrated measuring sticks that could read out a millimeter or less of squish or stretch, compression or tension, as a force was applied to a sample in the laboratory. The railroad manufacturing industry, in particular the design and construction of locomotives, was the chief market for strain-measuring instruments in the nineteenth century, evolving precisely machined devices that sometimes resembled slide rules that could in effect magnify a tiny amount of strain into readable values. For example, the Whittemore strain gauge that was often used in structures laboratories was originally developed by Baldwin Locomotive Works (Filiatrault 2003). See Fig. 7-1. Not much had changed from the nineteenth century until the invention of the electric resistance strain gauge, and today, that basic type of instrument is still ubiquitous in many engineering applications, and certainly in earthquake engineering laboratories.

The story of that invention, or co-invention, involves an early earthquake shake table, literally the size of a small table, namely the one in use in the laboratory of Professor Arthur Ruge (1905–2000) at the Massachusetts Institute of Technology. Ruge (rhymes with rupee) was funded by the insurance industry to do small-scale shake table tests on an elevated water tank, because damage to water supply could have a devastating effect in the context of earthquake-caused fires (Fig. 1-3). In 1937–1938, he pondered how to measure the invisible deformations of the scale-model metal water tank as it was being shaken, and he hit upon the idea of gluing some thin membrane, something like paper, to the metal so that it deformed as the

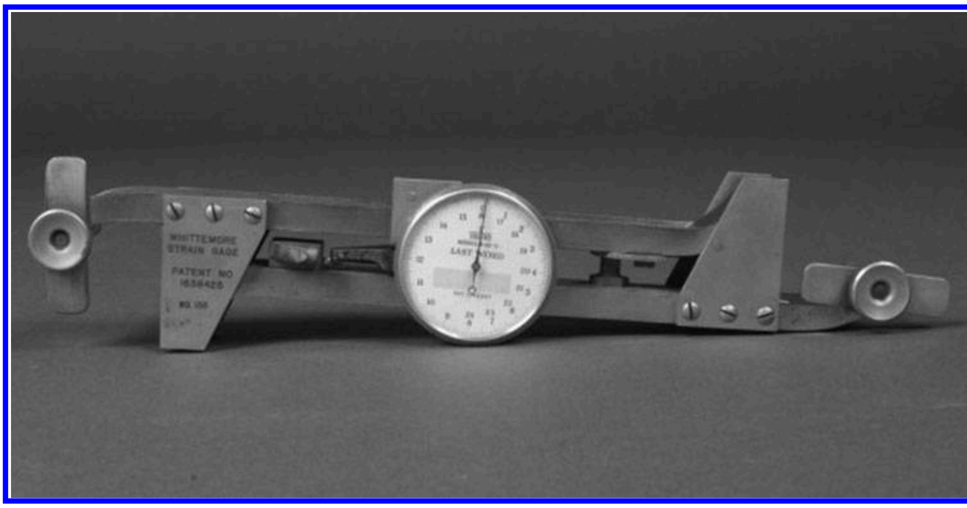

Fig. 7-1. Mechanical Whittemore strain gauge, top view. Precise conical points were fixed in tiny holes in the piece of steel whose elongation or shortening was to be measured. *Source: National Institute of Standards and Technology Digital Collections, Gaithersburg, MD 20899, reproduced with permission.*

metal did. Electric current going through that thin membrane would vary as the geometry varied, for example, as it stretched and resistance changed. This model evolved into a tiny labyrinth of wires—the device was smaller than a postage stamp and not much thicker—whose tiny deformations could be accurately measured in terms of electrical current. It turned out that a researcher at Caltech, Edward Simmons, had hit upon the idea in 1936 and also had a patent pending, in which effort he was successful, and the line of strain gauges ended up being called SR, for Simmons–Ruge. (Simmons was not an earthquake researcher; his strain gauge invention came from unrelated laboratory work.) The first model, SR-4, was manufactured by the company, Baldwin Locomotive Works, that had the line of mechanical instruments invented for the railroad industry, but just as it was brought to market, World War II was beginning and one of its first and most influential applications was in the airplane industry. Figure 7-2 illustrates a modern version of the electric resistance strain gauge.

The electric resistance strain gauge is a prime example of how direct analog measurements that were the rule up to about 1800 gave way to transducers, instruments that sensed one kind of energy and converted it into another kind, typically into an electrical signal. Because electricity can be shaved down into fine increments that are virtually infinitesimally small, as compared with the crudity of marking off intervals on measuring sticks and gauges, it greatly improved precision, or granularity, of measurements. The ancient search of alchemists for transmutation of elements proved out of reach, but scientists, engineers, and technicians from the 1800s through the 1900s attained an even more important type of transmutation via their transducers. The full potential of earthquake engineering instruments that used electrical

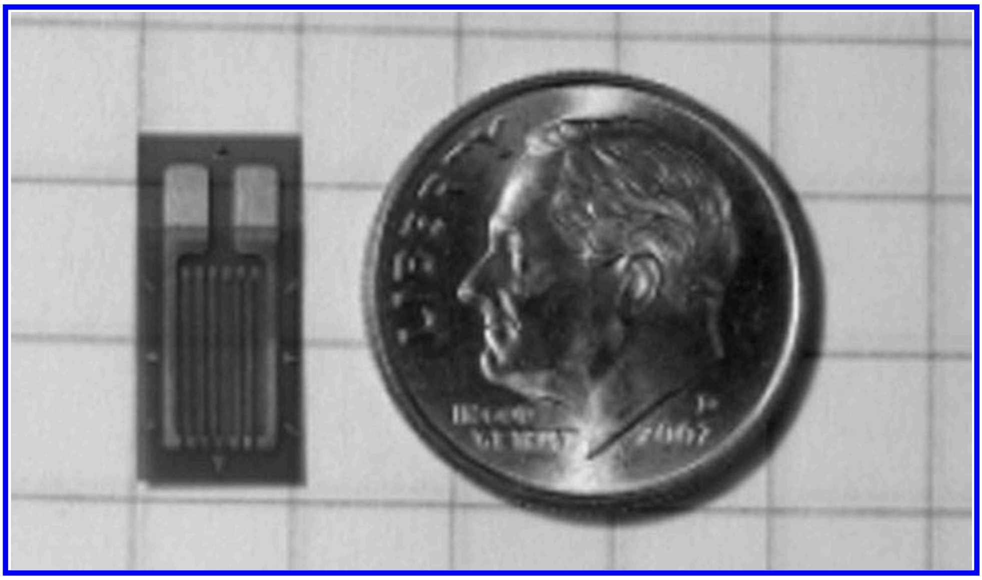

Fig. 7-2. Modern version of the Simpson-Ruge electric resistance strain gauge.
Source: CUREE, reproduced with permission.

means of sensing and recording data was only to be fully realized in the next era, 1960–2000, with the coming of the inexpensive but powerful digital computer. An electrical instrument can also deliver a stream of data over a period of time, unlike the manual process of using a mechanical gauge to measure change in distance (displacement) at one time, then reading another measurement at another time.

With the invention of the electric resistance strain gauge, the most common type of load cell directly measured strain and the result was converted into force. A cyclical alternation of an uplift force and a downward force occurs at one end of a wall subjected to lateral forces in the laboratory as it experiences an overturning moment. To measure these forces, a piece of steel can be attached to the edges of the wall, and measurement of the strain in that material can be converted to stress and thence to force. From Hooke's law, it is known that strain is proportional to stress within the elastic limit of the material, and because testing tabulates the stress/strain relationship for many materials, stress measurement can be obtained. Stress, F, is force, P, acting over an area, A. $F = P/A$, and hence $P = F \times A$. The cross-sectional area of the steel bar, A, is known, revealing what the force is. Although the beginning structural engineering student often thinks that force is the central concept in that discipline, strain in many cases takes center stage. In earthquake engineering, several parameters of great interest are related to strain: deflection (drift at the top level of a structure or interstory drift for a building); rotation (at a moment-resisting beam–column joint); distortion of an originally rectangular panel of material (a partition or shear wall deforming into a parallelogram); stiffness of individual members (to distribute lateral forces among vertically oriented elements at a given level); and stiffness of overall structure (to combine with mass to calculate period of vibration).

Filiatrault (2003) notes, "The first electrically based displacement system, developed in support of the aircraft industry, was the linear variable differential transformer (LVDT) patented by G. P Moadley in 1936 and marketed by M. Schaevitz in 1940. The LVDT is an inductive sensor whose voltage output is linear with displacement. It uses the motion of a plunger to modify its electrical output resistance." The basic concept underlying the device, discovered by Michael Faraday (1791–1867), was that a change in magnetic flux generates electrical voltage. When you slide your credit card through a machine to charge a purchase, the moving magnetic material on the card induces a voltage change that is amplified, and that code is deciphered by the reader. In an LVDT, the movement that generates current is the plunger as it is extended or withdrawn. The more coils it passes by in the core, the more current it generates. A related instrument for measuring change in length, for example, measuring the elongation of the tension side of a column as it deflects sideways in a test, is the DC current displacement transducer (DCDT), in which a wire pulls on a pistonlike core in the instrument, causing it to move, again involving generation of an electrical flux.

Developed for the aeronautics industry like the LVDT but invented later, as the 1940–1960 time period covered here was ending, is the string potentiometer, the "string pot," also known as a wire potentiometer or cable position transducer. One could crudely measure how much a test specimen is deflecting away from you if you hooked a fishing line to it and counted how many rotations of the reel occurred, relating those rotations to the linear distance the line extends. As the specimen deflected toward you and you reeled in the line, the opposite rotations could be used to measure the movement. One can precisely measure such change in distance if a wire is connected to a wheel, which, as it turns, causes a subtle change in electrical current to be measured. The wire itself, though lightweight, has mass and can be affected by inertial forces if it is riding along with a shaking specimen on a shake table or "taking a ride" on a centrifuge specimen, which can sometimes be a limitation.

Early applications of surveying instruments in the structures laboratory, such as the theodolite to visually measure change in position of a structural specimen, were made obsolete by the various electrical devices discussed above. However, toward the end of the twentieth century, optical surveying made a comeback in the structures laboratory in the form of such instruments as the RODYM system of visually tracking a grid of coordinates and precise digital photogrammetry devices for relating the change of positions of points on two photographs, changes caused by deformation. These systems have the advantage of making their measurements without touching the object. Figure 7-3 illustrates some of the instruments discussed above.

Within this 1940–1960 period, there was an interesting mechanical instrument invented specifically for earthquake engineering measurements. Though it seems to be a clever and useful instrument for tracking an important earthquake engineering

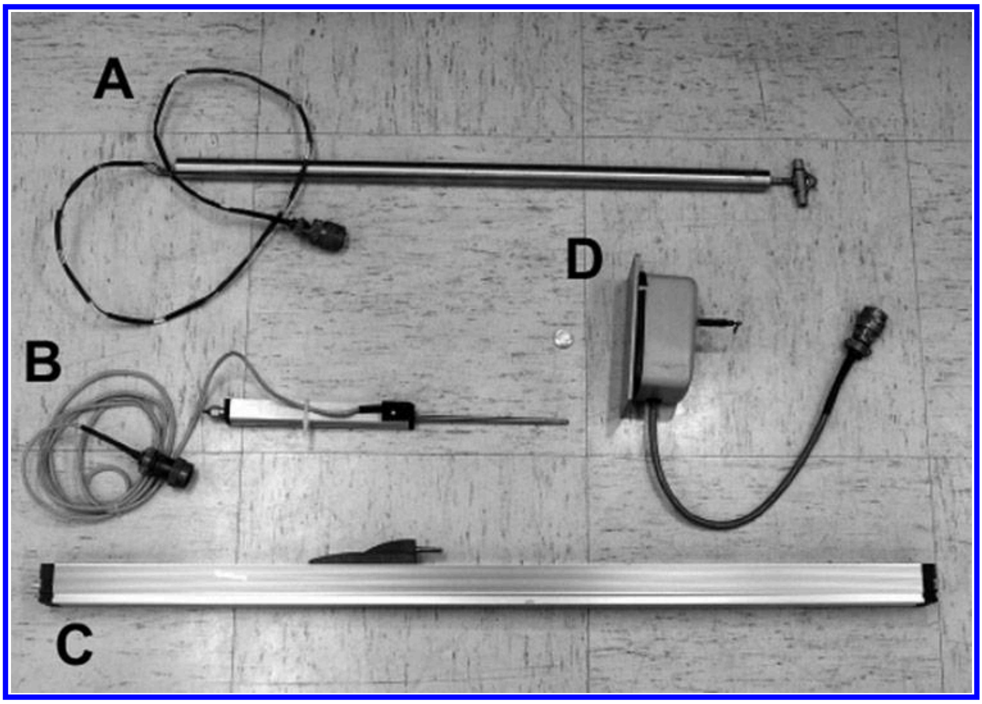

Fig. 7-3. Displacement-measuring instruments. (A) Linear variable differential transducer; (B) linear potentiometer; (C) another linear potentiometer model; (D) wire potentiometer ("string pot").
Source: CUREE, reproduced with permission.