The Science of Structural Revolutions [1]

William P. Graf, M.S., C.E.
URS Corporation, 915 Wilshire Boulevard, Suite 700
Los Angeles, California 90017 USA

ABSTRACT

A perspective on the very human process by which scientific paradigms change can help point the path forward in any science, or in an applied science, such as Structural Engineering. Understanding this process of change, we can examine earthquake engineering, seismic building codes and theories of structural engineering for earthquake loads.

When we take this perspective, we recognize that Structural Engineering for earthquake resistance is in the midst of a number of revolutions, from paradigms embodied in current building codes in which earthquake demands are associated with forces, to a new paradigm in which earthquake demands are re-envisioned as resulting from structural displacements or drift. The new paradigm is embodied in the current national standard for the seismic rehabilitation of existing structures, ASCE 41 [2] and the emerging standards for performance-based earthquake engineering (PBEE). Associated with this is the shift from design oriented towards life-safety to design for a range of performance objectives, such as life-safety, damage reduction, or immediate occupancy.

With this perspective, we further recognize deficiencies in research and development. We have failed to systematically use the experimental and computational tools we possess to fill in the gaps of scientific knowledge. We have not developed and deployed appropriate frameworks to collect and share ideas and results. As one example, the formulation of performance-based codes now outstrips the knowledge-base needed to ensure that structures designed by the new tools will meet their performance objectives.

Keywords: earthquake engineering, building codes, structural models, scientific method, paradigm shift.

1. OVERVIEW – STRUCTURAL ENGINEERING

Civil and Structural Engineers have the responsibility to design buildings and other structures to safely resist gravity, earthquake and other environmental loadings. Safe design depends on many factors. Among these are: technical understanding of the peril and resulting risks; appropriate and available technology and tools for analysis; the awareness of available, effective loss reduction measures; advocacy by disaster reduction "champions," and the occurrence of landmark disasters that mobilize the political will within this "primed" community. Moreover, successful risk reduction in the seismic area depends on consensus within the professional engineering community regarding the causes of damage and the technical means by which damage can be reduced. The technical, scientific understanding of earthquake hazards and the damage they cause in building structures is constantly evolving, affecting the response(s) of the technical scientific and engineering community, with potentially large repercussions in the public arena.

2. THE IDEAL OF SCIENCE

The ideal of the scientific method may be described as a cycle involving four steps: 1) observation, 2) synthesis, 3) hypothesis, and 4) prediction. Good science involves careful, systematic observations (measurements) by many observers under controlled, repeatable conditions, with comparison of results in some universal format. Data from many observers are compiled and compared, and patterns emerge that provoke questions. Hypotheses are formulated – models to explain the underlying processes, and these models in turn provide predictive power, to be tested by experiments or observations designed to discriminate between competing hypotheses. And the cycle goes on. When a hypothesis has been widely tested for generations and has been shown to be successful, it may be accepted as a scientific law, like Newton's laws of motion, or Hooke's law.

The success of science as an enterprise has prompted those engaged in the philosophy of science to suggest that science possesses some special character and occupies a privileged epistemic status. Many credit the scientific method as the source of this success and special status. Other possible unique features of science contributing to its unparalleled success include:

- The use of explicit models that make specific, falsifiable predictions.
- A tension between theory and experiment, providing a robust feedback loop and self-correcting mechanism.
- The use of instruments and precise measurement to extend the human senses and render observations quantifiable.
- The collaborative nature of science, wherein professional publications propagate new ideas and findings, and wherein professional organizations serve as vehicle to obtain funding and promote joint research for common problems facing the profession. Ideas are exchanged, and data and progress are actively shared – a feature well explained and promoted by Thomas Jefferson.

  "If nature has made any one thing less susceptible than all others of exclusive property, it is the action of the thinking power called an idea, which an individual may exclusively possess as long as he keeps it to himself; but the moment it is divulged, it forces itself into the possession of every one, and the receiver cannot dispossess himself of it. Its peculiar character, too, is that no one possesses the less, because every other possesses the whole of it. He who receives an idea from me, receives instruction himself without lessening mine; as he who lights his taper at mine, receives light without darkening me." *–Thomas Jefferson [3]*

- The competitive nature of science, wherein independent teams perform similar experiments. Results must be readily reproducible to be accepted.
- The use of symbolic and mathematical descriptions to supplement and extend the power of language, so that scientific theories and predictions are quantitative, rather than merely descriptive and explanatory. Other human activities (including some social sciences) readily more admit mere plausible rationalization as adequate.
- The use of quantitative models for design, control and prediction (with the potential for falsification).

3. THE REALITY OF SCIENCE

In one of the most influential books of the 20th century, **The Structure of Scientific Revolutions**, T.S. Kuhn [1] presents a more realistic view of the way in which science progresses. Many of the features of science outlined above have to do with "feedback loops" and precise testing of specific predictions. These feedback loops and self-testing mechanisms serve to identify anomalies – exceptions to the shared understanding and conventional wisdom referred to by Kuhn as the prevailing paradigm. Insistent and unavoidable anomalies precipitate revolutions, with the resulting rapid progress, new capabilities and new opportunities. Paradigm destroys paradigm. Scientific school eats school. Kuhn describes the messy, human path to progress.

The **Structure of Scientific Revolutions** can be seen as a cautionary tale, a story about "good" science and "bad" science, and how human weakness, pride and politics get in the way of scientific progress. Science is subject to the limits of human perception and the constraints of personality, society and sociology. Seen in this light, we may ask what needs to be done to better manage scientific revolutions, and how we can remain open to new theories while we continue to test all theories, new and old. Unlike the law, no case is ever fully proven. Kuhn's description of the cycle of change warns us against the safe and comfortable research project that advances nothing when founded on the unexamined pre-suppositions of an outmoded paradigm. More importantly, without effective feedback loops, without quantitative testing, we fail to detect anomalies, and we continue to use poor models and believe misleading theories.

4. ENGINEERING VS. SCIENCE

The challenges and constraints that apply to good science also apply to engineering, only more so. Industries fund research and help steer practice within the profession. Science often takes a back seat to economic interests and development.

Engineering is not science. Engineers care for theory only to the extent that it is useful for solving problems. Moreover, design engineers tend to avoid theoretical innovation, preferring solutions that are “tried and true.” Engineers like to focus on design -- the application of known paradigms. Engineering disciplines are more insulated than scientific disciplines. The average practitioner is not a scientist, and has trouble just keeping up with the ever-increasing complexity of codes, while confronting fixed or declining fees and shrinking schedules. Clients regard earthquake engineering as a ‘solved problem,’ and are reluctant to engage in research projects.

Another area in which Structural Engineering stands in contrast to science is statistics. As currently practiced, Structural Engineering rather stubbornly avoids uncertainty and statistics, adhering to deterministic approaches. This is in part pragmatic. Structural design of large structures is already complex and time-consuming, without modeling the uncertainties in loading, dynamic response, and failure mechanisms. This also reflects the determinism of Classical Mechanics – engineers prefer to believe that if the loading and structural systems are precisely known, then response can be calculated exactly. Finally, most Structural Engineers are not mathematicians – we don't like anything more complicated than $P/A + Mc/I$.

5. THE CASE OF STRUCTURAL / EARTHQUAKE ENGINEERING

Structural Engineering to resist earthquake loading, as currently practiced, fails to meet some of the high standards of science. It may be viewed as applied science, with a liberal helping of art thrown in. Structural Engineering institutionalizes its paradigms in codes, which do not emerge as scientific laws, but are enacted as legal regulations. Fiat supplants the scientific method. Structural Engineering is among the most tradition-bound of the engineering disciplines. The formation process is more formal and rigid. Theories are enshrined as building codes.

In Structural Engineering for earthquake resistance, the current ‘feedback loops’ from actual earthquakes are many, partial and poor. We get information on failures only, in the forms of photos of damage, damage descriptions and tabulations of “lessons learned.” These anecdotal findings are not well correlated to hazard levels, so we do not routinely test relationships between demand and capacity. Codes get changed to prevent observed failures in future earthquakes, but the revisions may overcorrect. Anecdotal feedback is too imprecise to detect anomalies, and therefore to challenge the current paradigms. Progress stalls.

Fortunately, we have laboratory experiments and continued progress in the development of theory. We have seen rapid progress in computational capability, and the ability to partially test ideas with conceptual models (an extension of the ‘thought experiment’). We also have the exchange of ideas with other sciences and other disciplines – for example, the advance of seismological and geotechnical models. In particular, the recent proliferation of ground motion measurements from around the world and the resulting improved predictive model models [4] point to the need for similar efforts to produce comparable progress in the structural/earthquake arena. We need better ways to test and prove our codes. We need a more complete and robust “feedback loop.”

Why? Because lives are at stake. Because businesses are at stake. Because large parts of our society are at stake. When terrorism threatens, we mobilize our police and military and we elevate the threat status and take painful steps to stop or mitigate loss. How have we become complacent to threats of equal magnitude and frequency, simply because they spring from the nature, rather than from human enemies?

6. HISTORICAL DEVELOPMENTS & PARADIGM SHIFTS IN STRUCTURAL / EARTHQUAKE ENGINEERING

Before exploring the revolutions we currently face, it is useful to look back over previous changes in structural / earthquake engineering.

- *F=ma* The building is viewed as an accelerating (rigid) body, with application of lateral force in proportion to mass.
- Buildings are seen as mechanical spring-mass-damper systems. This leads to the invention and use of ground motion spectra – a single-degree-of-freedom (SDOF) representation of structures – and the elaboration of the force-based paradigm, imported from mechanical engineering and shock/vibration analysis. A set of equivalent static lateral forces are applied at floor levels to represent earthquake demands.
- Earthquakes (1906, 1933, 1971, 1989,…) demonstrate the importance of site ground conditions and their effect on the amplitude, frequency and duration of earthquake ground shaking.
- With main-frame digital computers, multi-degree-of-freedom (MDOF) elastic models emerge, allowing consideration of the contribution of torsional response, "higher modes," etc.
- Damage to concrete buildings in the San Fernando Valley Earthquake (M6.7, 1971) brings recognition of the importance of ductile detailing for confinement of plastic hinges and column cores. Cyclical loading is emphasized in testing for ductile performance.
- Widespread microcomputer use supports the emergence of non-linear time-history analysis methods and the development of the requisite computational tools.
- Nonlinear static procedures are developed as a tool to understand the progressive failure of a structure and provide for adequate displacement capacity.
- Emergency management and insurance drive the growth of loss-prediction methods, providing ways to simulate regional damage, examine catastrophic consequences and test loss mitigation measures: (e.g., ATC-13 [5], HAZUS [6], ABV [7]).
- Codes require the use of a mathematical model to capture overall "system" behaviors [8], in addition to the behavior of individual elements or components.

Each of these ideas faced skepticism and resistance, with a tumultuous re-thinking of the existing paradigms.

Paradigms shifts are slow. Building codes are tough to change, not only because they embody the current paradigm, but because commercial and regulatory interests are at stake.

7. A SHORT LIST OF CURRENT CHALLENGES

Of course, we cannot see the end of the story from the middle. But we can outline a few of the current challenges. (Many more might be suggested). Some challenges require research or experimental work to develop data and tools. Others require a revolution in thinking.

The shift from force-based to displacement-based demand models. Current seismic life-safety codes (e.g., the International Building Code) rely on a linear model, with displacement directly related to force. We will refer to this as the 'force-based paradigm.' Under the current (inverse) procedure, we compute elastic demand directly from a code-specified ground motion spectrum, and divide by a response modification factor (the "R" factor) to obtain design-level forces. For the design event, the prescribed design strength, together with code-required design detailing and good construction, should produce a building that survives without collapse. Under current codes, we calculate elastic displacements, then amplify the displacements to account (very roughly) for nonlinearity and check for displacement compatibility of nonstructural elements.

Nonlinear procedures can account for the yield and failure of individual components within the lateral force-resisting system and their effect on the overall building response. Forces are redistributed as elements crack and yield, and the designer can provide for this redistribution through controlled, safe mechanisms. Since inelastic structural displacements are the primary performance variables within inelastic analysis, we will refer to this as the 'displacement-based paradigm.' Performance-based earthquake engineering (PBEE) follows this displacement-based paradigm.

The replacement of force-based seismic building codes with displacement-based codes may require a new generation of engineers, equipped with new concepts and training and tools.

Prove it! Looking back to seismic code procedures originating in the force-based paradigm, we acknowledge that R-factors – set by code committees – were never experimentally validated. That is, we have no formal proof that, when we divide elastic forces by the "magical" R-factor (introduced in the 1988 Uniform Building Code), we will end up with a structure that will not collapse in the code-level earthquake. The magnitude 6 to 7 earthquakes that we have had in the U.S. over the past 30 years have provided only partial validation. We contented ourselves with the expert opinions of code committees, and failed to systematically use the experimental and computational tools we possess to fill in the gaps of scientific knowledge. Nonlinear methods lead us suspect future structural failures of buildings designed using linear methods and traditional force-based codes, especially in large-magnitude earthquakes.

We have not developed and deployed universal frameworks to collect and share data, ideas and results. Remarkably few large buildings are seismically instrumented (unlike commercial aircraft, which must have 'black boxes'). Insurers hoard claims data, so repair costs are poorly known. Engineers study dramatic failures, but not the similar surviving building next door. University laboratories test components rather than realistic representations of older, hazardous buildings. Without a solid foundation of performance data, the formulation of performance-based codes now outstrips the knowledge-base needed to ensure that structures designed by the new tools will meet their specific performance objectives.

Ultimately, what we need is more instrumented buildings and sites, and the procedures / mechanisms / forums to collect and disseminate good data. By 'good data', we mean that we need to recover from real buildings in future earthquakes the type of data we would require in a good laboratory experiment. Input must be measured, by high-resolution recording of the motions at the base (foundation) of the structure. Outputs must be measured (floor accelerations and displacements). And the "system" being tested must be defined (we need an adequate model of the structure, its material properties, capacities of members and connections, as well as construction and repair cost data). Current digital technologies can easily provide robust instrumentation. Building structural models can be preserved from the design process. The expense is small, compared to the value of the people and the cost of the structures and processes we are protecting. But as a society we must set the priority and require the effort.

Measure It. In science, it is not enough to name a thing, you have to measure it. Technical terminology allows us to describe observable phenomena, but description does not suffice for prediction, much less for safe design. As engineers, we need to quantify performance, so we need predictive equations based on measurable, testable quantities.

The example below points to one current need in earthquake engineering.

For the same intensity of ground shaking (i.e., Sa), large-magnitude, long-duration earthquakes will cause more building damage and collapses than smaller earthquakes. Larger magnitude events force structures through a larger number of inelastic cycles, with greater degradation of strength and stiffness. While the earthquake engineering community acknowledges this magnitude-dependence, it is not reflected in current design building codes.

At present we have no simple and convenient way to estimate the number of response cycles that a particular ground motion may induce above a given threshold. The lack of a clear way to measure and communicate information about cyclic response has hindered research and development in many areas.

So let's invent one.

Current ground motion spectra [10] plot the maximum response of an SDOF oscillator for fixed period and damping levels to a time-history of ground motion. We construct conventional response spectra based on the maximum value of oscillator response. Right now, we keep only the maximum, n=1 time equaled or exceeded. But why not identify all the maxima, store the histogram of peak values, and construct a family of curves with:

n = 2 times equaled or exceeded
n = 5 times equaled or exceeded
n =10 times equaled or exceeded

This is illustrated in Figure 1.

What emerges is a new ground motion intensity measure we call "peak exceedance spectra" or "n-Spectra." For a given excitation motion, n-Spectra quantify how many times an elastic single-degree-of-freedom (SDOF) oscillator will exceed any given amplitude of response (e.g., Sa). An example is shown in Figure 2. The n=1 spectrum is identical to the conventional elastic response spectrum. At any period, the n-Spectra plot serves as a cumulative histogram of spectral response peak amplitudes. By quantifying the number of demand peaks (and hence cycles) above a level of interest, peak exceedance spectra provide a more complete estimator of the potential damage due earthquake ground motions. n-Spectra are easy to compute, they complement conventional elastic response spectra, and have many practical applications. Because of this, n-Spectra have the potential to become a very useful tool in earthquake engineering.

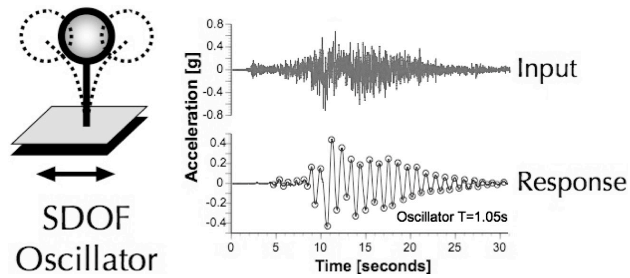

Figure 1. Identify All of the Peaks

For example, in structural analysis using nonlinear dynamic procedures (NDPs), peak exceedance spectra will provide a new means for specifying ground motion time series ("time histories" in earthquake engineering terminology) to ensure that the subject structure is exposed to a sufficient number of inelastic cycles for its seismic environment.

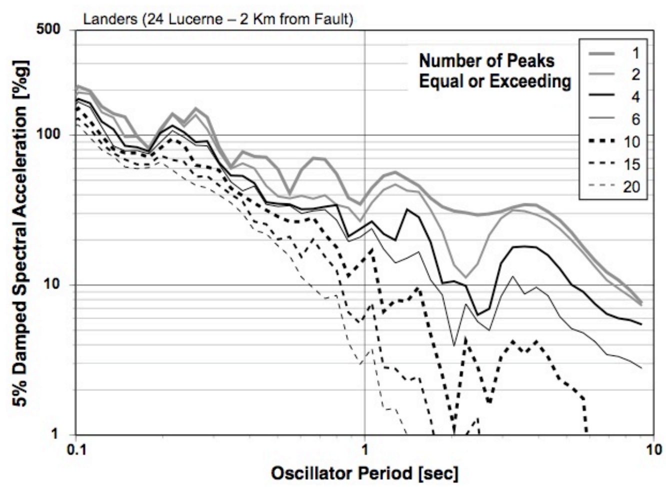

Figure 2. Peak Exceedance Spectra for the Lucerne Record from the 1992 Landers Earthquake [M7.3]

By providing a simple, direct way to quantify cyclic demand, peak exceedance spectra will inform loading specifications in component and structure testing protocols [9].

In geotechnical engineering, peak exceedance spectra provide a direct estimate of the number of cycles that a saturated layer of soil may experience above its shear strength.

In the context of performance-based earthquake engineering, peak exceedance spectra can be used to specify the number of cycles under which a component or structure (buildings, bridges, levees, etc.) must sustain its capacity for a defined target level of deformation (displacement).

In damage assessment techniques such as HAZUS, quantitative relationships may be developed between the number of cycles above yield and the degree of hysteretic degradation. This is currently prescribed by the Kappa factor, which is only roughly set by expert judgment.

Plots of n-Spectra relate Sa, T and “n” in a flexible framework. The relationship between the response level and number of exceedances (n) works both ways. For a given period, you can specify Sa and find “n,” or you can set “n” and find the corresponding Sa. In other words, at any structural period of interest, we can read the “n” values to see how many response peaks occur above any value of Sa. For a structure that yields or becomes fully plastic at a particular spectral acceleration, we can see how many inelastic cycles it must sustain without failure. For a saturated soil layer with a shear strength corresponding to a particular spectral acceleration at the site period, we can see how many failure cycles it will experience.

From the n-Spectra we have examined to date, we find that short-period oscillators (T<0.5s) show only modest reduction in Sa for large “n.” Long-period oscillators (T>1s) show large reduction in Sa as “n” increases. For structures that can be treated as a single-degree-of-freedom oscillator, the implications are important in terms of the trade-off between strength and toughness.

Of course, buildings are not elastic SDOF oscillators. Once a structure yields, its period and time-history of response change, compared to a structure that remains elastic. Buildings have multiple modes of vibration, so we must be careful in applying n-Spectra to buildings. Nevertheless, current codes (e.g., IBC [11]) treat “regular” buildings as elastic SDOF to specify minimum equivalent static lateral forces for seismic design.

N-Spectra provide the simple and convenient way we were lacking to estimate the number of response cycles that a given ground motion may induce above a given threshold. When you make a phenomenon explicit and can measure it, it enters the domain of science, and the concept can compete and combine with other ideas, to the benefit of all.

Unification of earthquake damage assessment methods and earthquake design methods.

As we move to performance-based earthquake engineering, it becomes important for all design engineers to be able to relate earthquake hazards to the expected performance of their designs in terms that the owner or developer can understand: dollars, downtime and death. It is not enough to say: “the design meets code.”

The ideal model for performance-based earthquake engineering would (modified from [12]):

1. Accommodate any ground motion as input.
2. Consider magnitude dependence through structural degradation and the duration of ground motion.
3. Model ductile and brittle elements.
4. Predict casualties, repair costs and downtime.
5. Quantify the reliability of its outputs
6. Have industry consensus.

These same objectives apply to damage assessment methods employed for regional risk studies and earthquake insurance. As the methods converge, the industries should collaborate and share data.

“Reliability-based design.”

At present, we design for life-safety using a point estimate of demand, and we neglect structural performance uncertainty. In other words, the code asks: “are building responses acceptable during the code-defined design event?” The question should be: “what is the probability of structural failure during the life of the structure, given its full seismic environment?” The full range of potential earthquake demands needs to be considered, and the probability for unacceptable performance quantified, accounting for the uncertainties in the performance of structural members and systems.

What is needed is “reliability-based” design, using probabilistic models that properly consider the full seismic environment (all future events and their probabilities), while considering endogenous uncertainties (variance in demand and capacity as represented within the model) as well as exogenous uncertainties (limitations to the model, and the uncertainties that remain even with “perfect” model parameters).

Such reliability-based design would clearly demonstrate the importance of both structural redundancy and active quality assurance. Some steps towards such methods have been made [13, 14, 15].

The restoration of elegance to seismic design codes.

A model should be as simple as possible, but not simpler.
– Albert Einstein

Codes and procedures need to be simple and straightforward. Jumbled paradigms lead to confused and complicated procedures.

Currently, structural design for earthquakes involves an assortment of codes: the International Building Code (IBC), another code for design loads [15], and additional codes for designing in the materials used in the gravity and lateral force-resisting systems (wood, steel, masonry, concrete, etc.). This array of disparate standards is inconvenient and confusing at best.

It is time for a re-write of the seismic design codes, from the ground up, based on the most robust understanding we have from the best paradigm – displacement-based methods.

Each code provision should have a comprehensive commentary explaining the relevance and importance of the provision, and connecting it to the research and experience from which it is drawn. This will provide meaning to the process, and point to needed research. It would also assist in the removal of outdated and irrelevant passages, as the science improves.

Recognition of the limitations of the technology provides another winnowing method. "Given all of the other uncertainties and imprecision, is this requirement material to safety or other performance objective?"

The application of technology and the principles of science may provide a path back to elegance. That which is difficult to manage in a hardcopy format is easier in a 'wiki' format. Electronic versions for the various codes and provisions could be linked and supplemented by metadata would allow collecting all relevant provisions in one place.

Selecting, for example, "new wood-frame residential design" could be used to collect all of the loading, capacity and prescriptive design provisions in one place, together with their commentaries.

8. ACKNOWLEDGING OUR LIMITATIONS

"The Map is not the Territory" [16]

One of the lessons of science is humility. The history of science ought to remind us that our understanding will inevitably evolve. Our 'map' of the earthquake behavior of the built environment is drawn from experience, from mathematical models and from laboratory experiments.

Seismological and structural engineering models help to inform us about certain aspects of structural behavior, and allow us to interpolate to the specific case, and to extrapolate from our experience to something more. There are many models, but only limited, noisy data to indicate which are best, or if any approach adequacy.

Laboratory experiments can test some aspects of some of the ideas we already have, discriminating between theories already formulated. The lab may produce a few surprises, but nature will always produce more. What we cannot conceive, we cannot test, but nature is not constrained by the human mind.

Our past experience -- the 'map' of earthquake history -- is limited. We believe that buildings designed and constructed under recent codes will perform well in great earthquakes, but we do not have a track record – yet. For example, we have not yet seen great earthquakes strike our dense city centers, so we do not know how well our very tall structures will perform. As another example, we have not seen how 5-story wood-framed buildings with plywood shear walls will perform, since these are a recent innovation. Very large tilt-up warehouses, with wood roofs as much as 2000 feet long, are another case. Here, the length of the building begins to approach the wavelength of the ground motions that excite it. The next earthquake may bring some unwelcome surprises.

9. CONCLUSIONS

In this paper, we contrast science and engineering, using the case of Structural Engineering for earthquake loads. Like science, engineering is rocked by revolutions brought about by changes in knowledge. Unlike science, engineering theories become enshrined as building codes, impeding their evolution.

Each new earthquake, each new analytical tool, each new testing program and each new structural system produce changes in the Structural Engineering practice for the design of buildings to resist seismic loadings. As we accommodate these changes, we should continually respect and promote good science in the pursuit of good engineering.

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