

Understanding Structural Engineering: From Science to Engineering

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ABSTRACT

This paper examines the major developments in the area of structural engineering within the last 70 years, and tries to draw the big picture of all these achievements in order to show the reader how they are connected. The different breakthroughs in the field of structural engineering, from science to engineering and from theory to practice, are illustrated, traced back to their origin and placed into prospective.

These developments are covered in a chronological order; first the fundamental laws of mechanics, followed by theory of elasticity, the development of the generalized stress-generalized strain concept and how this concept was reflected in making the elasticity theory more practical with the consequence of the working stress design method. Next, the era of plasticity is outlined with the need for idealization and simplification of the theory; thus leading to limit analysis with lower bound and upper bound theorems, plastic hinge concept and its application, yield line theory and strut-and-tie model.

The finite element method comes as an off spring of the generalized stress-generalized strain concept, principle of virtual displacement and shape function. It opened the door to solve any problem under any condition. In parallel the LRFD design comes to practice. Still yet, intuitive models from mechanics with simple calculations, such as the strut-and-tie model as an equilibrium solution, are necessary for understanding the behavior and design of concrete structures. For steel structures the advanced analysis comes as essential next step; which utilizes available computational capabilities and at the same time reduces the design effort with improved output. Finally, the era of computer simulation comes with a glance to the future.

The paper aims to illustrate how all these developments are connected and trace back to the same foundation. The key thoughts behind these developments for structural engineers are idealization and simplification.

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1. HISTORICAL SKETCH

The master builders, the designers, and constructors of the Gothic cathedrals of the Middle Ages used intuition and experience to develop design rules based on simple force equilibrium and treated the material as rigid. This solution process provided the equivalent of what is now known as the lower bound theorem of plastic limit analysis. That theorem was not proved until more than 500 years later. Modern lower bound theorem shows that these design rules are safe. These simple design rules have existed from the earliest times for building Greek temples, Roman aqueducts and arch bridges, domes and vaults. However, tests on real structures showed that the stresses calculated by designers with these rules could not actually be measured in practice.

Galileo, in the 17th century, was the first to introduce recognizably modern science into the calculation of structures; he determined the breaking strength of beams but he was way ahead of his time in engineering application. In the 18th century, engineers moved away from his proposed “ultimate load” approach, and until early in the 19th century, a formal philosophy of design had been established: a structure should remain elastic, with a safety factor on stress built into the analysis. It was an era of great advance and a milestone in structural design but one that placed too much of its emphasis on the undue safety concern based on elastic response under working loads.

Galileo Galilei (1564-1642) was the first to use mathematics in order to describe the law of nature which is based on observation from experiments. Isaac Newton (1642-1727) discovered the basic laws of physics in terms of equilibrium condition (or equation of equilibrium) and equation of motion. Robert Hooke (1635-1703) described, in mathematical form, the material response to stress, which he observed in tests. He stated the linear relation between stress and strain (Hooke’s law or constitutive law) as a function of a material constant (elasticity modulus or Young’s modulus).

Material continuity without discontinuities or cracks is a logical assumption in solid mechanics. This assumption leads to a mathematical description of geometric relations of a continuous medium known as *continuum* expressed in the form now known as compatibility conditions. For a continuum, the conditions of equilibrium (physics), constitutive (materials) and continuity (geometry) furnish the three sets of basic equations necessary for solutions in any solid mechanics problem in which structural engineering is one of its applications. In short, the mechanics analysis of a given structural problem or a proposed structural design must involve the mathematical formulation of the following three sets of equations and solutions:

- Equilibrium equations or motion reflecting laws of physics (e.g. Newton’s laws)
- Constitutive equations or stress-strain relations reflecting material behavior (experiments)
- Compatibility equations or kinematical relations reflecting the geometry or continuity of materials (logic)

The inter-relationship of these three sets of basic equations is shown in Fig. 1 for the case of static analysis.

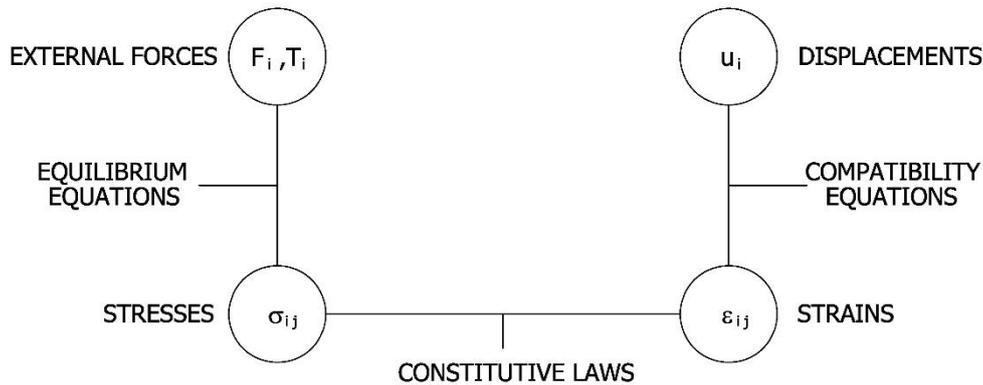


Fig. 1 Interrelationship of the three sets of basic field equations.

2. THE FUNDAMENTALS OF STRUCTURAL ANALYSIS

The basic step of structural analysis is the application of these three sets of equations of equilibrium, compatibility, and constitutive laws. They are the fundamentals for all methods of structural analysis. In general, the three sets of basic conditions are expressed in terms of 15 equations: three equilibrium, six compatibility, and six constitutive equations. The solution of these 15 simultaneous equations should provide solutions for six stresses, six strains and three displacements at a point in the structure system under consideration. It is the role of mathematics to achieve the solutions of these equations (Sokolnikoff, 1956).

In principle the solution of the 15 equations for 15 unknowns is possible from mathematical point of view. However, for real world applications, structural engineer must operate with ideal material models and ideal structural systems to reduce drastically the 15 unknowns. The theories of reinforced concrete design, for example, do not deal with real reinforced concrete. They operate with an ideal composite material consisting of concrete and steel, the design properties of which have been approximated from those of real reinforced concrete by a process of drastic idealization and simplification. The same process of simplification and idealization also applies to the formulation of the basic equations of equilibrium and compatibility of real structural system.

The breakthroughs that made the difference in the development of structural engineering are, most notably, the following concepts and theorems.

- The generalized-stresses and generalized-strains concept connects the conventional strength-of-materials approach to a continuum-mechanics-based theory of elasticity and plasticity, leading to the modern development of finite-element solutions in structural engineering.
- The proof of the limit theorems of perfect plasticity provides rational principles for preliminary structural design via simple equilibrium or kinematical processes consistent with engineers' intuitive approaches to design, leading to the modern development of strut-tie models for structural design in reinforced concrete in particular.

- The simple plastic-hinge concept enables the direct application of simple plastic theory to steel-frame design in particular, leading to the modern development of advanced analysis for structural design in steel.

Computer simulation has now joined theory and experimentation as a third path for engineering design and performance evaluation. Simulation is computing, theory is modeling, and experimentation is validation. The major challenges for future structural engineers are the integration and simplification of material science, structural engineering and computation and then make them work and applicable for the real world of engineering.

3. ELASTIC ANALYSIS AS A START

To simplify the field equations for a realistic engineering solution, it is more convenient to formulate the elastic or plastic relations in terms of elements from which the parts of the structure are composed rather for the material treated as a mathematical point as defined elegantly in the concept of continuum mechanics. For example, for a structural member such as beam in a building framework, the basic element or segment can be obtained by cutting through the entire thickness of beam section. Thanks to this approach, it is then possible to replace the six stress components acting on the cross section of the element by one dominant normal stress resultant – the bending moment, M (generalized stress). Similarly, the corresponding six deformational components can be reduced to one dominant strain resultant – the angle of relative rotation or curvature, ϕ (generalized strain).

This concept of using the generalized stresses and generalized strains for inelastic structural analysis and design was employed for the first time in 1952 by Prager in establishing his general theory of limit design, and later in 1959, utilized prominently by Hodge in his popular text on the plastic analysis of structures. It took great insight to fully understand the impact by unifying the conventional strength of materials approach to the modern theory of plasticity and limit design in a consistent manner.

The relationship between the value of bending moment M and the angle of relative rotation ϕ at the ends of the segment represents the material behavior of that structural element (generalized stress-generalized strain relation, Fig. 2b). The relationship is linear and reversible for a linear elastic material, as observed by Hooke, before yielding or cracking under working load condition. With this simplification, it has become possible to develop solutions for structural members and frames. These solutions so obtained are called *strength of material* solutions. Thanks to this simplification, the complex local stress and strain states in a real sizable element of a real structure are avoided and the field of application of the theory of elasticity and the field of application of the theory of plasticity can be broadened significantly. This expansion and generalization resulted in the development of modern structural theories, among them several structural elements including bar elements, plate elements, shell elements and finite elements.

This study and mathematical formulation of engineering structures have led to a formal three-stage process in mechanics operation as summarized in the following:

- First, the relations between stresses in a structural element and the generalized stresses acting on the surface of the element are determined by the use of equilibrium equations.
- Second, the relations between deformations of the material in the element and the generalized strains on the surface of the element are established through a kinematical assumption such as “plane section before bending remains plane after bending”.
- Finally, the generalized-stresses generalized-strains relations are derived through the use of stress-strain relations of the material.

4. PLASTIC ANALYSIS AS A FURTHER PROGRESS

The idealization of elastic-perfectly plastic behavior of material beyond the elastic range opened the door to a new era of mechanics. Introducing this idealization in the formulation of generalized stress-generalized strain relation led to several advanced relations of structure elements. For instance, the elastic-perfectly plastic uniaxial stress-strain relation in Fig. 2a leads to the generalized stress-generalized strain relation (moment-curvature relation) of cross-section shown in Fig. 2b. This moment-curvature relationship must be further idealized in order to develop simple plastic theory for engineering practice. This leads, for example, to ignoring strain hardening and also to eliminating entirely the effect of time from the calculations. This further idealization is illustrated in Fig. 2c, leading to the concept of *plastic hinge*, Fig. 2d by ignoring further the relatively small elastic strains near collapse of a structure. This further idealization of perfect-plasticity to deal with the complex plastic behavior of the structural element gives powerful limit theorems of plasticity (Drucker et al., 1952), which made it possible to estimate the collapse load of a variety of structure systems including beams, plates and shells in a direct manner.

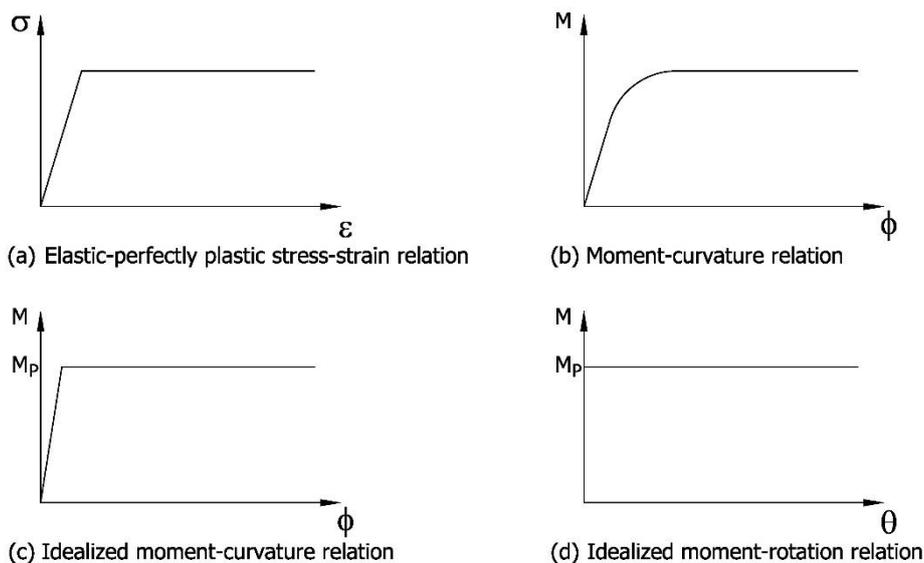


Fig. 2 Development of plastic hinge concept.

The upper and lower-bound theorems of limit analysis of perfect plasticity provide an excellent guide for preliminary design as well as for analysis of structures.

- *Lower-bound theorem.* If an equilibrium distribution of moment can be found which balances the applied loads, and is everywhere below plastic moment or at the plastic moment value, the structure will not collapse or will just be at the point of collapse.
- *Upper-bound theorem.* The structure will collapse if there is a compatible pattern of plastic-failure mechanism for which the rate at which the external forces do work equals or exceeds the rate of internal dissipation.

The lower-bound theorem states that the structure will adjust itself to carry the applied load if at all possible. It gives lower-bound or safe values of the collapse loading. The maximum lower bound is the collapse load itself. The upper bound theorem states that if a plastic failure mechanism exists, the structure will not stand up. It gives upper-bound or unsafe values of the collapse loading. The minimum upper-bound is the collapse load itself.

Historically, engineers in the past, based on intuition, developed many solutions for weak-tension material (based on equilibrium only) and for ductile materials (based on kinematics only), which have now been justified by the rigorous theorems of limit analysis. The theorems of limit analysis thus represent a very powerful tool nowadays to estimate the collapse load of structures or structural members without having to go through a very tedious calculation procedure.

In the case of lower bound solution of limit analysis, only equilibrium and yield criterion are satisfied; equilibrium is satisfied for stress or generalized stress. The crude solution so obtained represents a good and quick guidance for the structural engineer. It can be used to verify some refined solutions from other methods. The lower bound method is especially useful for application to tension-weak material; e.g., stones or concrete. Hence, the safety of monumental structures such as cathedral can be checked very well with such a method.

In the case of upper bound solution only kinematics and yield criterion are satisfied. The method is very powerful for ductile material and even applicable to material with limited ductility but with some modification of the solution procedure. The quick estimate of the collapse load of a structure is of great value, not only as a simple check for a more refined computer analysis, but also as a basis for preliminary engineering design. The method, for example, can be used to make a quick check to verify solutions obtained from some sophisticated finite element analysis in particular.

The structural applications of the limit theorems started with the development of the simple plastic theory for steel building design (Neal, 1957) and were extended to the development of yield line theory for reinforced concrete slab design (Nielsen, 1964). Limit theorems have been explored carefully for applications to stability problems in soil mechanics (Chen, 1975), complemented by applications to the metal-forming process (Johnson, 1986) and studied thoroughly in metal-matrix-composites applications (Dvorak et al., 1982), among others.

5. FINITE ELEMENT ANALYSIS AS A LOGICAL EXTENSION

The development of the finite-element analysis was a logical extension of the mechanics analysis involving mathematical formulation of the three sets of basic equations and solutions as described previously. First, the concept of generalized stress and generalized strain allowed dealing with a finite element instead of a material point in a structure. Second, the principle of virtual work was utilized for the formulation of equilibrium instead of force balance, which simplified the solution process significantly. Third, by assuming an appropriate shape function of an element, compatibility between strains in the element to its nodal displacements was conveniently justified. These simplifications made it possible to obtain engineering solutions of almost any structure of any geometry and of any material model.

The finite element method with powerful computers enabled engineers to implement realistic geometry and accurate material models into the analysis. Hence, it has become possible to obtain not only the collapse load of a structure but also the deformations under any loading level including even the post-peak behavior. As a result, it has become possible to apply the theory of stability with the theory of plasticity to simulate the actual behavior of structural members and frames with great confidence. It was the first time we were able to replace the costly full-scale tests with computer simulation. As a result of such progress, together with a rapid advancement in computing power, large amounts of numerical data were generated in a variety of structural engineering applications during this era.

The following is a brief summary of the kind of numerical data that were generated through the finite-element analysis for structural members and frames in the 1970's. As a result of these data, the limit-state approach to design was advanced and new specifications in steel design were issued in the 1980's.

1970's – Numerical studies of member-strength equations:

- Beam-strength equation leading to beam design curve.
- Column-strength equation leading to column design curve.
- Beam-column-strength equation leading to beam-column-interaction design curve.
- Bi-axially-loaded-column strength equation for plastic design in steel building frames.

These developments were summarized in the two-volume treatise by Chen and Atsuta (1976, 1977).

1980's – Limit states to design:

- Development of reliability-based codes.
- Publication of 1986 AISC/LRFD specification in USA (AISC, 1986) and Europe (ECCS, 1984).
- Introduction of second-order elastic analysis to design codes.
- Explicit consideration of semi-rigid connections in frame design (now known as "partially restrained construction") in USA (Chen and Kim, 1998) and Europe (ECCS, 1992).

These developments were summarized in the book by Chen and Lui (1992).

6. STRUT-AND-TIE MODEL AS A POWERFUL TOOL

With the advancement in material modeling and finite element idealization, the computational process has become more powerful but also more complicated and time consuming. For every day practice it is necessary to rely on simplified analysis but with adequate accuracy. The lower-bound and upper-bound solutions of limit analysis serve this purpose realistically and conveniently. The equilibrium method has been used since ancient times as in the Egyptian Pyramids, structures of arched form and monumental structures. The recent proof of this method supports the ancient engineering practice and helps expand the method to modern applications of reinforced concrete structures.

One of the most important advances in reinforced concrete in recent years is the extension of lower-bound-limit-theorem-based design procedures to shear, torsion, bearing stresses, and the design of structural discontinuities such as joints and corners. The *Strut-Tie-Model (STM)* is developed for such a purpose and is based on the lower-bound theorem of limit analysis. In this model, the complex stress distribution in the structure is idealized as a truss carrying the imposed loading through the structure to its supports. Like a real truss, a strut-and-tie model consists of compression struts and tension ties inter-connected at nodes. Using the stress legs similar to those sketched in Fig. 3, a lower-bound stress field that satisfies equilibrium and does not violate failure criteria at any point can be constructed easily to provide a safe estimate of the load-carrying capacity of the reinforced-concrete structures (Chen and Han, 1988).

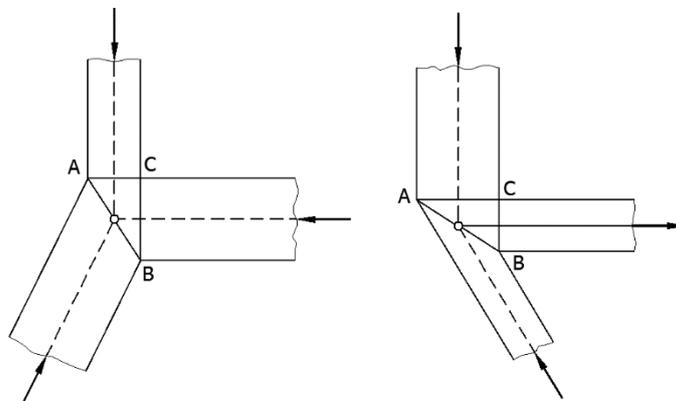


Fig. 3 Use of stress-legs as truss members to produce a stress field at a stress joint.

The *STM* has been well developed over the last three decades and the subject has been presented in several texts as a standard method for shear, joints and support bearing design. The *STM* method was also introduced in the AASHTO LRFD Specifications (ASCE, 1998 and AASHTO, 1998) as well as in the ACI 318 building code (ACI 318-14). A typical example of strut-and-tie model for a common structural joint design is sketched in Fig. 4.

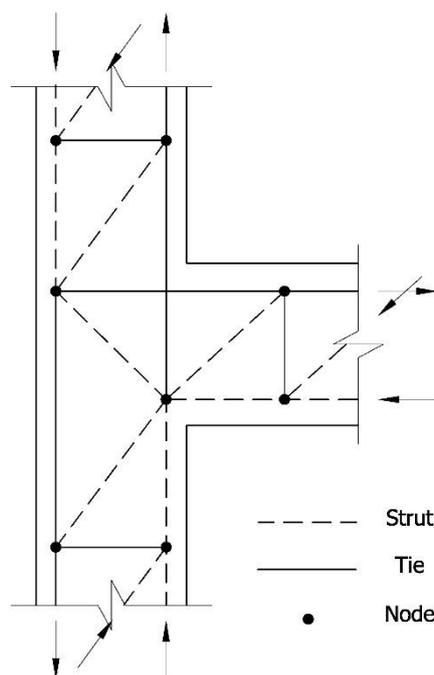


Fig. 4 Application of the STM to reinforced concrete joint design.

Strut-and-tie models are derived from the flow of forces within structural concrete regions, namely, those of high shear stresses, where Bernoulli hypothesis of flexure, plane sections before bending remain plane after bending does not apply. Those regions are referred to as discontinuity or disturbance regions (or simply D-regions), in contrast to those regions where Bernoulli hypothesis is valid, and are referred to as Bernoulli or bending regions (or simply B-regions). The flow of forces in D-regions can be traced through the concept of truss, thus named truss model or strut-and-tie model which is a generalization of the truss model.

7. ADVANCED ANALYSIS FOR STEEL FRAME DESIGN AS THE CURRENT PROGRESS

In current engineering practice, there is a fundamental two stage process in the design operation:

- The forces acting on the structural members are determined by conducting an elastic structural system analysis, and
- The sizes of various structural members are selected by checking against the ultimate strength equations specified in design codes.

The interaction behavior between individual members and their structural system is accounted for approximately by the use of the effective length factor K concept as illustrated schematically in Fig. 5. However, despite its popular use in current practice as a basis for design, the effective length approach has the following major limitations:

- It cannot reflect the inelastic distributions of internal forces in a structural system,
- It cannot provide information on the failure mechanisms of a structural system,

- It is not easy to implement in an integrated computer design application, and
- It is a time-consuming process by calculating every K factor for each separate member capacity check.

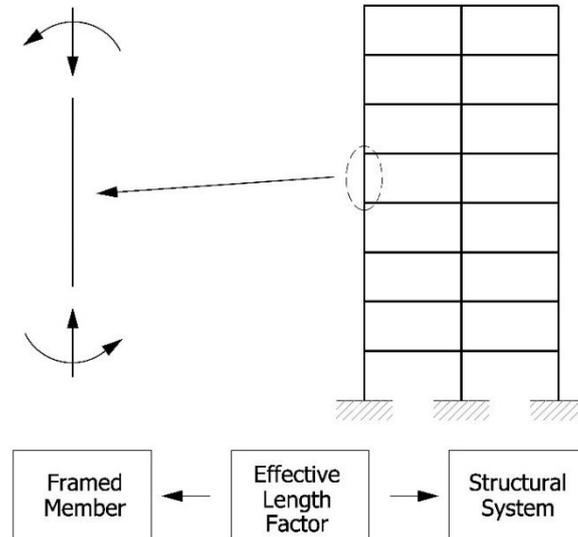


Fig. 5 Interaction between a structural system and its component members using the K factor concept.

Furthermore, some of these difficulties are more so on seismic designs since additional questions are frequently asked:

- How is the structure going to behave during an earthquake?
- Which part of the structure is the most critical area?
- What will happen if part of the structure yields or fails?
- What might happen if forces greater than the code has specified occur?

Considering these limitations and drawbacks and the rapid advancement of computing power, the second-order inelastic analysis approach or so-called *advanced analysis* approach provides an alternative approach to structural analysis and design. Nevertheless, this approach consumes tremendous computation efforts and in order to overcome such a demand the practical advanced analysis has been developed (Chen, 2009). The practical advanced analysis is an elastic-plastic-hinge-based analysis, modified to include the geometry imperfections, gradually yielding and residual stresses effects, and semi-rigid connections. In this approach, all those aforementioned drawbacks associated with using K factor are overcome. There is no need to compute the effective length factor, yet, it will produce almost identical member sizes as those of the LRFD method (Chen and Kim, 1997).

8. COMPUTER BASED SIMULATION AS THE FUTURE TREND

We are now in a desktop environment for unlimited computing. Computer simulation has now joined theory and experimentation as a third path to scientific

knowledge. Simulation plays an increasing critical role in all areas of science and engineering. Exciting examples of these simulations are occurring in areas such as Automotive Crash-Worthiness for component design in auto industry, Boeing 777 for system design and manufacturing in aerospace, and the next generation Space Telescope (Hubble II) for system design, assembly, and operation in space engineering. One key branch of this new discipline is *model-based simulation* (MBS), whose objective is to develop the capability for realistically simulating the behavior of complex systems under the loading and environmental conditions that the systems may experience during their lifetimes.

Simulation does not replace observation and physical experimentation but complements and enhances their value in the synthesis of analytical models. It provides a framework for combining theory and experimentation with advanced computation. Besides, massive numerical computations, high performance computers permit the use of other tools, such as visualization and global communications using advanced networks, all of which contribute to the ability to understand and to control the physical processes governing complex systems.

Model-based simulation is based on the integration of mechanics, computing, physics and materials science for predicting the behavior of complex engineering and natural systems. MBS allows engineers and researchers to investigate the entire lifecycle of engineered systems and assist in decisions on the design, construction, and performance in civil and mechanical systems. Reliable and accurate MBS tools will permit the design of engineering systems that cost less and perform better.

The emerging areas of model-based simulation in structural engineering will notably include the following topics:

1. From the present structural system approach to the life-cycle structural analysis and design covering construction sequence analysis during construction, performance analysis during service, and degradation and deterioration analysis during maintenance, rehabilitation and demolition.
2. From the present finite element modeling for continuous media to the finite block types of modeling for tension-weak materials which will develop cracks and subsequently change the geometry and topology of the structure.
3. From the present time-independent elastic and inelastic material modeling to the time-dependent modeling reflecting material degradation and deterioration science.

These emerging areas of research and application are inherently interdisciplinary in science, and engineering, where computation plays the key role. Scientists provide a consistent theory for application, and structural engineers must continue to face the reality of dealing with idealizations of idealizations of these theories in order to make them work and applicable to the real world of engineering.

9. SUMMARY

Over the last few decades, remarkable developments have occurred in computer hardware and software. Advancement in computer technology have spurred the development of structural calculations ranging from the simple strength of materials approach in early years, to the finite element type of structural analysis for design in

recent years; and to the modern development of scientific simulation and visualization for structural problems in the years to come. Table 1 summarizes briefly the “major advances” of structural engineering that can be attributed to the “breakthroughs” of mechanics formulation, material modeling or computing power where new knowledge has been implemented in structural engineering and, in some measure; the structural engineering practice has been fundamentally changed. These “success stories” fall into one of the following three categories: *mechanics, materials, and computing* as tabulated briefly in Table 1 below.

Table 1 The Interaction of mechanics, materials and computing and the advancement of structural engineering practice

Mechanics	Materials	Computing	Structural Analysis and Design
Strength of materials formulation: closed form solutions by series expansion, numerical solutions by finite difference	Linear elasticity	Slide rule and calculator environment	Strength of Materials Approach to Structural Engineering in the Early Years: <ul style="list-style-type: none"> ○ Allowable stress design with K factor. ○ Amplification factor for second-order effect. ○ Moment distribution or slope deflection methods for load distribution in framed structures. ○ Member by member design process. ○ Design rules based on allowable strength of members from tests with built-in safety factors.
Limit analysis methods: mechanism method, and equilibrium method, plastic hinge concept	Perfect plasticity	Slide rule and calculator environment	Simple Plastic Analysis Method for Steel Frame Design in the Early Years: <ul style="list-style-type: none"> ○ Plastic analysis and design with K factor. ○ Amplification factor for second-order effects. ○ Upper and lower bound methods for frame design. ○ Member by member design process. ○ Design rules based on ultimate strength of members from tests.
Finite element	General plasticity	Mainframe computing	Finite Element Approach to Structural Engineering in Recent

<p>formulation using shape function and virtual work equation: generalized stresses and generalized strains concept</p>		<p>environment</p>	<p>Years:</p> <ul style="list-style-type: none"> ○ Development of member strength equations with probability and reliability theory. ○ Development of reliability-based codes. ○ Limit states to design with K factor. ○ Direct calculation of second-order effect. ○ Member by member design approach. ○ Design rules based on load factor and resistance factor concept by mathematical theory.
<p>Advanced analysis: combining theory of stability with theory of plasticity</p>	<p>General plasticity</p>	<p>Desktop computing with object-oriented programming</p>	<p>Second-Order Inelastic Analysis for Direct Frame Design as the Current Progress:</p> <ul style="list-style-type: none"> ○ Structural system approach to design without K factor and amplification factor. ○ Explicitly consideration of the influence of structural joints in the analysis/design process. ○ Development of performance-based codes. ○ Consideration of “structural fuse” concept in design. ○ Design based on maximum strength of the structural system without having to carry out member by member strength check.
<p>Model-based simulation based on the integration of mechanics, computing, physics and material science</p>	<p>Deterioration science or aging</p>	<p>High performance computing</p>	<p>Large Scale Simulation of Structural System over Its Life-Cycle Performance Analysis:</p> <ul style="list-style-type: none"> ○ Numerical challenges: proper modeling of discontinuity and fracture or crack for tension-weak materials. ○ Software challenges:

			<p>radically different scales in time and/or space.</p> <ul style="list-style-type: none"> ○ Material challenges: from time independent elastic and inelastic material model to time-dependent modeling reflecting material degradation and deterioration science. ○ Design process includes modeling (physics), simulation (computing), visualization (software) and verification (experiment).
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A topic on which significant progress has been made in recent years is the determination of the load-carrying capacity of structures through the application of the theory of plasticity. This is in contrast to the earlier era design with undue emphasis on linear elastic analysis. Engineering specifications contained rules that help engineers avoid most of the errors of overdesign or under-design with guidelines derived from experience and tests. However, rules based on past experience work well only for designs lying within the scope of that range. They cannot be relied on outside of that range. Ideally, the design guidelines and rules should be derived from sound physical and mathematical principles.

Similar to the theory of elasticity in earlier eras, the theory of plasticity in later years provides one of these success stories of applied mechanics that leads to the development of modern design guidelines and rules. The mathematical theory of plasticity enables us to go beyond the elastic range in a time-independent but theoretically consistent way for inelastic structural analysis and design.

The introduction of the concept of generalized stresses and generalized strains for structural elements and the establishment of the general theory of limit analysis and design in the 1950's laid the foundation for the revolution in structural engineering in subsequent years. The adoption of plastic analysis methods in steel specifications started the revolution in the 1960's. Thanks to the rapid advancement of computing power beginning in the 1970's, the study of mechanics and mathematical formulation subsequently focused on the study of structural elements from which the parts of the structure are composed rather than for material itself. Thanks to this approach, the field of application on the theory of plasticity to structural engineering has broadened appreciably.

In the more recent years, various analysis approaches to the estimation of stress, strain and displacement including analytical, numerical, physical and analog techniques have advanced and are readily available to the engineering profession. In particular, the finite element technique is the most versatile and popular. As a result of this success, design specifications around the world have been undergoing several stages

of revolutionary changes from the allowable stress design, to plastic design, to load-resistance factor design, and to the more recent performance-based design.

We are now in a desktop environment for unlimited computing. Computer *simulation* has now joined the *theory* and *experimentation* as a third path for engineering design and performance evaluation. Simulation is computing, theory is modeling, and experimentation is validation of the results. As a structural engineer, we must continue to face the reality of dealing with idealizations of idealizations of these science-based theories in order to make them work and applicable to the real world of engineering. Seeing the big picture of our past achievements in structural engineering will enable us to make a difference in the further advancement of structural engineering in the years to come.

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