Justifiable Precision and Accuracy in Structural and Civil Engineering Calculations

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Abstract

As a result of technological progression, mathematical calculations may currently be carried out to levels of precision which are orders of magnitude greater than were possible only decades ago. Consequently, design professionals are producing structural engineering calculations to unrealistically high levels of precision. Many engineers advocate the reporting of structural design calculations to four, five, and even six significant figures, with disregard to the implicit precision on which modern design codes and specifications are based.

In response to these expectations, historical documents pertaining to structural design have been reviewed, methods of structural analysis have been considered, and practical design situations have been reviewed in order to remind the structural engineer of the inherent limitations of the precision of structural engineering calculations. Conclusions have been drawn from these considerations, and a recommendation with respect to an appropriate level of precision in structural design is presented.

Introduction

During the course of the last one hundred years, structural engineers have conformed to constantly changing standards for design, fabrication, and erection of buildings and other structures. Since the late 19th century, design codes and specifications have been introduced, applied, and revised to both meet changing load demands and construction materials and take into consideration a better understanding of environmental factors and structural response.

Until the mid-1970's, engineers used slide rules as their basic tool for engineering calculations. Using a typical 10-inch slide rule, an engineer could report an answer to three significant figures, four at the left end of the rule (Petroski 1985). That engineer could accurately read an answer to two or three digits, respectively, and could estimate the third or fourth depending on the position of the reference point between the two certain limits. Such calculations were said to be made to "slide rule precision". During the 19th and 20th centuries, before the advent of pocket calculators, structures were analyzed and designed to "slide rule precision", including monumental structures such as the Empire State Building, Eiffel Tower, Brooklyn Bridge, and George Washington Bridge. Amazingly, calculations made using slide rules during the "space race" between the former Soviet Union and the United States sent men into orbit around the earth and to the moon and back. Engineers from both the Soyuz and Apollo flight teams accepted "slide rule precision" for many of their revolutionary achievements.

With the advent of the pocket calculator in 1972, calculations could be carried out orders of magnitude more precisely. Even the first common calculator, the HP-35, could display eight digits on its LED interface. Few engineers immediately began using pocket calculators, as many preferred the slide rule to which they had been accustomed. In fact, many early calculators were referred to as "electronic slide rules". Over time, the reliability and convenience of calculators became obvious, and by the early 1980s calculators were used with greater frequency than slide rules. As engineers calculated loads and resistances to eight and even twelve figures, the precision of such calculations was thought by many to be greater, but in fact, engineers were slowly losing sight of the significance of digits and the resultant precision in their work.

Accuracy versus Precision

A clear distinction must be drawn between accuracy and precision. From an engineering standpoint, most general-purpose dictionaries do not provide adequate definitions of these terms for engineering application. The IEEE Dictionary of Electrical and Electronic Terms (IEEE, 1997) reports as follows (emphasis by authors):

> **Precision.** The quality of being exactly or sharply defined or stated. A measure of the precision of a representation is the number of distinguishable alternatives from which it was selected, *which is sometimes indicated by the number of significant digits it contains*.
>
> **Accuracy.** The quality of freedom from mistake or error, that is, of conformity to truth or to a rule. Note: Accuracy is distinguished from precision as in the following example: *A six-place table is more precise than a four-place table. However, if there are errors in the six-place table, it may be more or less accurate than the four-place table.*

American Society for Testing and Materials (ASTM) standard E29-93a, “Standard Practices for Using Significant Figures in Test Data to Determine Conformance with Specifications”, specifies practices for making numerical calculations and reporting results therefrom. This standard, although not specifically pertaining to structural engineering calculations, sets a precedent for reporting such calculations to an acceptable level of precision. Section 7.4.1.2 specifies “The rule when multiplying or dividing is that the result shall contain no more significant digits than the value with the smaller number of significant digits” (ASTM 2002e). Furthermore, ASTM E29-93a states, “The significance of trailing zeros for numbers represented without use of a decimal point can only be identified from knowledge of the source of the value.” The aforementioned specifications suggest that the result of a numerical calculation is no more precise than the least precise element of the calculation; in other words, the chain is only as strong as its weakest link.

Structural Design Methodology

Any structural design calculation, whether performed in accordance to Load and Resistance Factor Design (LRFD) or Allowable Stress Design (ASD) for steel, or Ultimate Strength Design (USD) for concrete, follows a simple form whereby the structure must be designed to resist the forces to which one predicts it may be subjected.

$$\text{Load Effect} \quad \leq \quad \text{Structural Resistance} \qquad (1)$$

That is, the effect of loads for which the building is designed must be less than or equal to the resistance that such building will provide. More specifically, each member and connection must be able to withstand the forces to which it will be subjected.

Since 1923, designers of steel structures have predominantly followed the American Institute of Steel Construction's (AISC) ASD methodology, where members are elastically proportioned such that allowable stresses are not exceeded when the structure is subjected to service loads. That is:

$$f(\sum Q_i) \leq F_{ALLOW} \, ; \tag{2}$$

where $f(\sum Q_i)$ = elastic stress arising from appropriately combined nominal loads, and F_{ALLOW} = limiting stress (yield, buckling, shear, tension, bearing, etc.) divided by a factor of safety (AISC 1923).

Since the introduction of the LRFD method for steel buildings in 1986, some engineers prefer to use this approach. The LRFD methodology is based upon ultimate strength limit states of strength combined with first-order probability analysis. The LRFD formula relates the resistance of a structure to the load acting on it by the following relationship:

$$\sum \lambda_i Q_i \leq \phi R_n \, ; \tag{3}$$

where Q_i = load effect, λ_i = load factor, R_n = nominal resistance, and ϕ = resistance factor (AISC 1986).

In parallel with trends in steel design, two structural concrete design philosophies were presented by the American Concrete Institute (ACI). Initially, Working Stress Design (WSD) was the predominant method used from the early 1900's until the 1960's (Ghosh et al. 1996). With the introduction of the 1956 ACI code (ACI 318-56), a prototype concrete design method was introduced and permitted: USD. With the release of the 1963 edition of the ACI code (ACI 318-63), USD became the primary design methodology and engineers have become familiar with USD and implemented this methodology into their design strategy. Such rapid transition has caused the USD method, also known as Strength Design (SD) Method, to become the predominant structural concrete design methodology.

The ACI's USD method, like the American Institute of Steel Construction's (AISC) LRFD method, incorporates ultimate strength considerations with first-order probability analysis. The ACI specification primarily addresses issues of ultimate strength, but also contains serviceability provisions for deflection and crack control (Ghosh et al. 1996). The criteria for USD follow the same form as the AISC LRFD, where the factored resistance of a structure must be greater than the factored load to which the structure is subjected.

An efficient engineer must understand both design methodology, which dictates the calculations necessary to design a structure, and also the methods with which to make and report such calculations.

Building Live Loads

In developing design loads for a building, an engineer must consider sustained loads due to a structure's dead weight; seismic loads due to the earth's surface shifts, environmental loads due to wind, rain, and snow; and finally "live loads" due to transient loads within the structure. The sustained (dead) load of a structure may be calculated with reasonable accuracy, while environmental and seismic loads acting on the same structure will exhibit great variability over time and may sometimes disappear altogether. A structure's live (transient) load may not be predicted with as much certainty as its dead load, but may be estimated with greater certainty than seismic and environmental loads. Nearly every structural engineering calculation must take into account live loading, certain in presence, but inherently uncertain in magnitude. Since every structure must resist live load, this paper addresses the precision and accuracy of live loads and their effect on structural calculations, as one omnipresent "link" in the calculation chain.

The 1924 guideline issued by the National Bureau of Standards, "Minimum Live Loads Allowable for Use in Design of Buildings", listed recommended minimum live loads for use in structural design. This guideline specified that for private dwellings and similar structures the live load shall be taken as 40 pounds per square foot (psf). Similarly, the guideline recommended a 250 psf live-load for storage areas, a 100 psf live-load for garages, and a 50 psf live-load for office buildings (DOC 1924). Furthermore, the 1924 guideline allows for the reduction of live loads by 10, 20, 30, 40, or 50 percent when designing girders, walls, columns, foundations, or trusses. An interesting question arises: How were these values derived? Little information is available to explain the process by which the original building code committee of the National Bureau of Standards determined the live loads and live load reductions. One may hypothesize an empirically-based approach, whereby existing floor loads in common buildings were estimated.

After examining the most current building load specification, ASCE 7-10, "Minimum Design Loads for Buildings and Other Structures", an engineer will note that still, after eight decades of research and revision since the 1924 National Bureau of Standards (NBS) guideline, the vast majority of live loads are specified in even multiples of ten, and therefore to either two or three significant figures (ASCE 2010). Although the ASCE 7-10 document contains minimum live load specifications for many more specific occupancies than the original 1924 National Bureau of Standards document, one will certainly note distinct similarities. For example, ACSE 7-10 specifies the minimum live load for “offices” as 50 psf, identical to the 1924 NBS document. Furthermore, ASCE 7-10 specifies the minimum live load for “dwellings” as 40 psf, identical to the 1924 building code specification for “private dwellings and similar structures”.

Many current minimum live loads are identical to those specified in the 1924 NBS document, although modern measurement and calculation techniques allow load measurement to greater accuracy and calculations to be carried out to eight or even more digits of precision. The significance of any digit after the third is neglected in ASCE 7-10, as it was in 1924.

Load Combinations

One must additionally consider the load factors by which loads are multiplied in determining a final design load for a structure. A structural engineer first determines individual values for dead load, live load, and various environmental loads and then applies load factors to each individual value through the use of an appropriate load combination. Such load combinations are specific to the methodology used to design the structure.

For example, ASCE 7-10 requires the following load combination to be used in calculating a final structural design load:

$$Q_i = 1.2(D + F + T) + 1.6(L+H) + .5(L_r \text{ or } S \text{ or } R); \qquad (4)$$

where Q_i = factored load effect, D = dead load, F = fluid load, T = self-straining force, L = live load, L_r = roof live load, S = snow load, and R = rain load. Similarly, the current USD specification for concrete, ACI 318-11, requires the following load combination to be used:

$$U = .75(1.2D + 1.6L + 1.6W) \qquad (5)$$

where U = factored load effect, D = dead load, L = live load, and W = wind load. One should note that the above load combination equations, regardless of the source, feature load factors of only two significant figures.

Structural Design Specifications: Steel

Since the early 1900's, structural design specifications have evolved from simple design suggestions into extensive documents based on intricate research. From the original AISC ASD specification (AISC 1923) to the current LRFD specification (AISC 1999), these guidelines have become increasingly complex. Due to such substantial evolution over a relatively short time period, limitations of the accuracy and precision contained in both design specifications should be examined.

For instance, both steel design specifications feature the use of factors of safety in their respective design methodologies to account for uncertainties in material properties, design theory, and construction practices. These factors appear in the form of "resistance factors" for LRFD and "allowable stresses" for ASD. The LRFD methodology specifies resistance factors ranging from $\phi = .75$ to $\phi = 1.0$ and the ASD methodology specifies allowable stresses such as $F_{allow} = .60F_y$ and $F_{allow} = .66F_y$, where F_y is the yield stress of the structural steel (AISC 1989b; AISC 1999). Both LRFD reduction factors and ASD allowable stresses contain two significant figures, thus, using ASTM E29 as a guide, an engineering calculation made in accordance to either of these specifications may contain only two significant figures.

Furthermore, the Seventh and Eighth Editions of the ASD Manual, published in 1973 and 1980, respectively, feature a distinct discrepancy in the suggested calculation of the nominal resistance of ASTM A36 steel. Specifically, ASTM specifies the yield strength of ASTM A36 steel as $F_y = 36$ ksi (ASTM 2002a). Several design equations within the ASD specifications contained in the manuals use an allowable design stress value of $.60F_y$ (AISC 1969; AISC 1978). These ASD specifications, in Appendix A, Table 1, list the value as .60 x 36ksi = 22 ksi. When properly evaluated, .60 x 36 ksi = 21.6 ksi. This inconsistency introduces an error in accuracy of .4/22, or approximately 1.8%, into any structural engineering calculation based upon these ASD specifications of the nominal resistance of 36 ksi steel.

The Ninth Edition of the ASD Manual, published in 1989, features a revised specification which lists 21.6 ksi, in Table 1 as the result of exactly the aforementioned nominal resistance calculation (AISC 1989a; AISC 1989b). Perhaps the authors of the earlier editions of the ASD specification chose to accept the numerical discrepancy and resultant loss of accuracy due to considerations of the level of slide rule precision to which engineering calculations were made. Such rounding, from 21.6 ksi to 22 ksi, suggests that, in accordance to ASTM E29, the inherent precision of the result of nominal resistance calculations made in conformance with the Seventh and Eighth Editions of the ASD specification should not exceed two significant figures (ASTM 2002e).

Earlier editions of the ASD and LRFD Manuals feature another inconsistency that introduces accuracy error into engineering calculations. ASTM specifies the yield strength of ASTM A53 steel pipe as 35 ksi, but the Seventh and Eighth Editions of the ASD Manual and the First and Second Editions of the LRFD Manual suggest the use of the provided 36 ksi design tables (AISC 1973; AISC 1980; AISC 1994; ASTM 2002b). The appropriate 35 ksi design tables were not provided until the Ninth Edition of the ASD Manual and the Third Edition of the LRFD Manual (AISC 1989a; AISC 2001). The suggested use of the 36 ksi tables for design with 35 ksi steel introduces an error in accuracy of 1.0ksi, or approximately 2.8%, into calculations based upon the Eighth and earlier editions of the ASD Manual and First and Second Editions of the LRFD Manual.

In addition to examining the limitations of precision to which steel structures may be designed, one must also address limitations pertaining to the level of precision to which the actual resistance of such structures may be reported. Since most steel limit states are a function of yield stress, ASTM E8, Standard Test Methods for Tensile Testing of Metal Material, is significant. In particular, the standard specifies that steel strength test results should be rounded to the nearest 100 psi (ASTM 2002d). Considering that steel yield stress values typically fall between 30,000 psi and 80,000 psi, rounding these values to the nearest 100 psi suggests precision of three significant figures.

Analysis of accepted inconsistencies in building codes governing steel construction and the limitations of precision to which steel structural strengths may be reported suggest acceptable levels of structural design calculation precision. AISC's ASD and LRFD specifications feature inconsistencies that suggest an acceptable precision of two significant figures, and the governing American standard for the testing of structural steel, ASTM E8, specifies an acceptable precision of three significant figures.

<u>Structural Design Specifications: Concrete</u>

Parallel to the organization of guidelines for steel construction, members of the construction industry recognized a need for the development of similar specifications pertaining to reinforced concrete. In 1941, ACI established the first concrete "building code", "Building Regulations for Reinforced Concrete (ACI 318-41)" (ACI 1941).

ACI 318-41 introduces the Working Stress Design methodology by stating "the design of reinforced concrete members shall be made with reference to working stresses and safe loads" (ACI 1941). ACI 318-41 specifies allowable unit stresses in concrete for specific types of loading in the form:

$$Cf'_c, \tag{6}$$

where f'_c is the 28-day compressive strength of concrete and C is an appropriate reduction factor. Table 305(a), of ACI 318-41, lists C values for different types of stress: .45 for flexural stress, .02 - .12 for shear stress, and .04 - .056 for bond stress (ACI 1941). These reduction factors contain two significant figures, thus, using ASTM E29 as a guide, the corresponding allowable stress may contain only two significant figures.

Furthermore, ACI 318-41 specifies allowable unit stresses in tensile steel reinforcement: 20,000 psi for rail and intermediate and hard grades of billet and axle steel reinforcement bars and 18,000 psi for structural grade billet and axle steel reinforcement bars (ACI 1941). Like allowable compressive stresses, maximum tensile stresses also contain only two significant figures.

The 1956 ACI code (ACI 318-56) recognized and permitted the use of the USD methodology, whereby "the design strength of a member at any section should equal or exceed the required strength calculated by the code-specified factored load combinations" (ACI 1995; ACI 2011). The USD methodology specifies the design strength of structural concrete as the nominal limit-state strength multiplied by a reduction factor, ϕ . The most current specification, ACI 318-11, lists reduction factors ranging from 0.65 to 0.90, depending on the limit state under consideration (ACI 2011).

Finally, consider the limitations on reporting the as-built resistance of a reinforced concrete structure as a function of the actual material strength. Since each of the various limit states of reinforced concrete depend upon the 28-day compressive strength of unreinforced concrete, consider the standard methodology for testing compressive strength of concrete specimens. The standard test method, specified by ASTM C39-01, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," consists of "applying a compressive axial load to molded cylinders or cores at a rate which is within a prescribed range until failure occurs (ASTM 2002c)." The maximum compressive strength of the specimen is determined by dividing the maximum load carried by the specimen by the average cross-sectional area of the specimen. ASTM C39 specifies that, for cylinders with compressive strengths between 2000psi and 8000psi, the strength should be recorded to the nearest 10psi, or, using ASTM E29 as a guide, three significant figures.

Furthermore, an engineer must realize the inherent variability in concrete strength due to the variability of the materials and methods with which the concrete is manufactured and it's effect on accuracy. Specifically, the compressive strength of a concrete specimen depends on the size and shape of the specimen; concrete batching and mixing procedures; methods of sampling, molding, and fabrication; and the age, temperature, and moisture conditions held during the curing of the specimen (ASTM 2002c). ASTM specifically addresses such variability in ASTM C39, section 4.2, stating "care must be exercised in the interpretation of significance of compressive strength determination by this method since strength is not a fundamental intrinsic property of concrete made from given materials."

In accordance with ACI 318-02 and ASTM E29, the governing reinforced concrete design specification and American standard for reporting of test results, respectively, the design strength of reinforced concrete should not be reported to a level of precision greater than two significant figures. Furthermore, according to ASTM E29 and ASTM C39, the American standard for testing of concrete specimens, the as-built resistance of a reinforced concrete structure should not be reported to a level of precision greater than three significant figures.

Methods of Analysis

A structural engineer may utilize a variety of tools available to conduct a structural analysis. An analysis may be carried out using pencil and paper, or the process may be automated by using computer software developed for such purposes. In choosing either option, the engineer bases his or her solution on the models and assumptions on which the analytical method may be based. Before an analysis may be conducted, the structure itself must be simplified using such models and assumptions. Geometrically complex structures must be broken down into a less complex form often consisting of simple members and connections. Assumptions must be made as to the stiffness of these structural members and the rigidity of the connections by which they are connected. The stiffness of a member is represented as a function of the cross-section of the member and its material properties; that is its moment of inertia and cross-sectional area, and modulus of elasticity, respectively. Member-to-member and member-to-foundation connections, typically bolted or welded in the structure itself, are represented as either fixed, hinged, or partially restrained connections. A structural engineer makes many assumptions as he or she models an actual structure using these simplifications, and therefore he or she must recognize the limitations of such models and the accuracy limitations of analytical results produced therefrom.

As an example of the limitations of structural models, consider the example of a simple portal frame subject to a uniformly distributed gravity load, illustrated in Figures 1a and 1c. The frame was analyzed using a commercial software package using stiffness analysis for two extreme conditions of base fixity: fixed and pinned. The analysis produces values for member bending moments, and diagrams of such are presented in Figures 1b and 1d. Analysis of the fixed-base frame yields member bending moments at the foundation, knee, and ridge as 43.3, 103, and 30.0 kip-ft, respectively. Identical analysis of the pinned-base frame yields member bending moments of 0, 107, and 38.7 kip-ft, respectively. Aside from the obvious differences in bending moment at the frame's base, note the 4 kip-ft difference at the knee and 8.7 kip-ft difference at the ridge.

As no structure's foundation connection is truly "fixed" nor "pinned", one may assume that the values of bending moments of an identically designed and loaded portal frame with realistic base conditions lie between the aforementioned values. An engineer should note that the basic assumptions made regarding the models of this simple structure caused a variance (with resulting questions as to accuracy) of the bending moments at the knee and ridge of 6.8% and 29%, respectively.

In an attempt to streamline the design process, structural engineers often implement approximate methods of analysis in the design of small structures. Approximate methods are simplified versions of the complex procedures with which one would analyze a more complex structure. These methods allow the engineer to produce cost-effective designs while not compromising the safety of the structure. Implementation of such methods leads to increased efficiency of design and analysis of the structural components of buildings, but the prudent engineer must be aware of the inherent limitations of results produced by an even further simplified method of analysis.

The Portal Method is considered an acceptable method of analysis for lateral loads (PCA 1993). This PCA publication suggests methods for simplified design of reinforced concrete buildings of moderate size and height based upon design specifications of ACI-318. The portal method of analysis features distinct simplifications regarding structural frames under lateral load: direct axial stress is taken by end columns only, the direct axial stresses in center columns is equal to zero, at any horizontal plane the wind load is divided proportionally among all the columns according to stiffness, and the point of inflection of columns is at midspan.

The aforementioned simplifications allow for efficient analysis, but significant discrepancies may exist between the portal method solution and an exact solution. As an example, consider the three-story, three-bay frame scenario presented in "Simplified Design" and illustrated in Figures 2a and 2b (PCA 1993). The fixed-base frame is subject to lateral wind loads and analysis is conducted using both the simplified portal method and an exact method of analysis. Beam bending moments as calculated by the portal method are reported for story one, story two, and the roof of the first bay as 90.3, 47.0, and 12.2 kip-ft, respectively (PCA 1993). The same moments as calculated by an exact analysis method are reported as 76.3, 47.7, and 17.6 kip-ft, resulting in differences of 14.0, 0.7, and 5.4 kip-ft respectively. One should realize that while the use of the simplified portal analysis may save time and therefore result in a more time-efficient design, the results differ from the "exact" solution by 18%, 1.5%, and 31%, respectively. The prudent engineer will exploit the advantages of simplified design methods while recognizing their inherent limitations with respect to design accuracy.

Practical Design Example

Engineers should be familiar with the aforementioned limitations that limit the level of precision to which one may make design calculations. Nevertheless, structural design engineers are often met by unreasonable expectations with respect to the precision and accuracy of their work. Consider a simple, but non-trivial, example of such expectations as encountered by the author.

The case involves the precision of calculations pertaining to the design of stairs, handrails, and guardrails for access to the elevator machine room according to the 2001 Florida Building Code; Pipe Railing Systems Manual, Third Edition; and Metal Stairs Manual, Fifth Edition; all current standard design specifications (FBC 2001; NAAMM 1992; NAAMM 1995).

After calculating the guardrail design load based upon the minimum distributed and point loads allowable by the 2001 Florida Building Code, 50 pounds per linear foot (plf) and 200 pounds, respectively, the author designed the railing based upon the allowable bending stress of the specified ASTM A53 pipe material, F_b=25,200psi (ASTM 2002b; FBC 2001; NAAMM 1995). The resulting design, illustrated in Figure 3, featured a 48-inch span between posts and maximum bending stresses for end and intermediate handrail posts as f_b=12,918psi (rounded to 12,900psi) and f_b=25,836psi (rounded to 25,800psi), respectively. The former maximum bending stress value falls well below the maximum allowable while the latter exceeds the maximum allowable by 2.48%. The engineer of record rejected the handrail design based upon this overstress.

Structural engineers must design based upon the current design specifications and building codes; they must also rely on personal experience to efficiently design safe structures. As noted by the designer for the aforementioned case, “It is a long accepted structural engineering design practice (for over 100 years) to accept small local overstresses (on the order of less than 5%) if the result of not accepting this overstress would be to produce substantial or unreasonable changes to the design”. In these cases, reporting calculations to more than three significant figures, or designing to supposed accuracy greater than 5%, proves excessive considering the design methodology and load variability.

Conclusion and Recommendation

The prudent structural engineer must consider economics and other intangible factors of design. Recognition and proper understanding of the history of structural design facilitate such consideration, as the design of structures in which we live is a function of basic human needs and the basic laws of nature. Structures respond to load today as they have since the first structures were designed, yet improvements in science and technology continuously change the methods by which these structures are designed. Since the 1950's, structural engineers have used computers to accelerate the design process, and since the 1970's pocket calculators have become a widely used design tool (Salvadori 1980). These technological improvements have revolutionized the face of structural design practice, but have also caused many engineers to lose sight of the basis of the problem to be solved.

The incredible speed and precision of modern computers has caused an increasing dependence on these machines, which, in time, may lead to a designer unaware of the technological foundation of structural engineering. Engineers must take responsibility to understand the limitations of precision to which structures should be designed as a function of the limitations of design codes, specifications, and methodology.

Evidence has been presented and examples have been shown which suggest that structural design calculations carry an inherent level of precision which is determined by the specific design methodology used to make such calculations and the variability of the building materials to which these calculations are applied. Through investigation into the historical foundation of minimum live load specifications, structural design methodology, and calculation tools, sufficient material has been presented to suggest that structural design calculations be reported to a maximum of three significant figures, or approximately 5% accuracy. Through the analysis of a practical example, one should note the unfortunate trend toward more stringent expectations with respect to the supposed precision of such calculations. Upon consideration of the material presented herein, the structural engineer must consider these inherent limitations in precision and conduct his or her practice accordingly.

References

ACI Committee 318. (1995). *Building Code Requirements for Structural Concrete: ACI 318-95); and Commentary (ACI 318R-95)*, American Concrete Institute, Farmington Hills, MI.

ACI Committee 318. (2011). *Building Code Requirements for Structural Concrete: (ACI 318-11) and Commentary (ACI 318R-11)*, American Concrete Institute, Farmington Hills, MI.

American Concrete Institute (ACI). (1941). *Building Regulations for Reinforced Concrete (ACI 318-41)*, American Concrete Institute, Detroit, MI.

American Institute of Steel Construction (AISC). (1923). *Steel Construction*, American Institute of Steel Construction, New York, NY.

American Institute of Steel Construction (AISC). (1969). *Specification for the Design, Fabrication, & Erection of Structural Steel for Buildings*, American Institute of Steel Construction, New York, NY.

American Institute of Steel Construction (AISC). (1973). *Manual of Steel Construction: Allowable Stress Design*, New York, NY.

American Institute of Steel Construction (AISC). (1978). *Specification for the Design, Fabrication, & Erection of Structural Steel for Buildings*, American Institute of Steel Construction, Chicago, IL.

American Institute of Steel Construction (AISC). (1980). *Manual of Steel Construction*, American Institute of Steel Construction, Chicago, IL.

American Institute of Steel Construction (AISC). (1989a). *Manual of Steel Construction : Allowable Stress Design*, American Institute of Steel Construction, Chicago, IL.

American Institute of Steel Construction (AISC). (1989b). *Specification for Structural Steel Buildings*, American Institute of Steel Construction, Chicago, IL.

American Institute of Steel Construction (AISC). (1994). *Load & Resistance Factor Design : Manual of Steel Construction*, American Institute of Steel Construction, Chicago, IL.

American Institute of Steel Construction (AISC). (1999). *Load and Resistance Factor Design Specification for Structural Steel Buildings*, American Institute of Steel Construction, Chicago, IL.

American Institute of Steel Construction (AISC). (2001). *Load and Resistance Factor Design: Manual of Steel Construction*, American Institute of Steel Construction, Chicago, IL.

American Society for Testing and Materials (ASTM). (2002a). " A36/A36M-03a Standard Specification for Carbon Structural Steel." Annual Book of ASTM Standards, ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). (2002b). "A53/A53M-02 Standard Specification for Pipe, Steel, Black and Hot-Dipped, Zinc-Coated, Welded and Seamless." Annual Book of ASTM Standards, ASTM, Philadelphia, PA.

American Society for Testing and Materials (ASTM). (2002c). "C39/C39M-01 Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens." Annual Book of ASTM Standards, ASTM, Philadelphia, PA., 18-22.

American Society for Testing and Materials (ASTM). (2002d). "E8/E8M Standard Testing Methods for Tensile Testing of Metal Materials." Annual Book of ASTM Standards, ASTM, Philadelphia, PA, 68-74.

American Society for Testing and Materials (ASTM). (2002e). "E29-93a Standard Practice for Using Significant Digits in Test Data to Determine Conformance with Specifications." Annual Book of ASTM Standards, ASTM, Philadelphia, PA., 19-22.

American Society of Civil Engineers (ASCE). (2010). *ASCE 7-10, Minimum Design Loads for Buildings and Other Structures*, American Society of Civil Engineers, Reston, VA.

Department of Commerce: Building Code Committee (DOC). (1924). *Minimum Live Loads Allowable for Use in Design of Buildings*, National Bureau of Standards, Washington D.C.

Florida Building Commission (FBC). (2001). *Florida Building Code*, The Florida Building Commission, Tallahassee, FL.

Ghosh, S. K., Fanella, D. A., Rabbat, B. G., and Portland Cement Association. (1996). *Notes on ACI 318-95, Building Code Requirements for Structural Concrete : With Design Applications*, Portland Cement Association, Skokie, IL.

IEEE. (1997). *IEEE Dictionary of Electrical and Electronic Terms*, IEEE.

National Association of Architectural Metal Manufacturers (NAAMM). (1992). *Metal Stairs Manual, 5th Edition*, National Association of Architectural Metal Manufacturers, Chicago, IL.

National Association of Architectural Metal Manufacturers (NAAMM). (1995). *Pipe Railing Design Manual (ANSI/NAAMM 521-95)*, National Association of Architectural Metal Manufacturers, Chicago, IL.

Petroski, H. (1985). *To Engineer Is Human : The Role of Failure in Successful Design*, St. Martin's Press, New York, NY.

Portland Cement Association (PCA). (1993). *Simplified Design: Reinforced Concrete Buildings of Moderate Size and Height*, Portland Cement Association, Skokie, IL.

Salvadori, M. (1980). *Why Buildings Stand Up: The Strength of Architecture*, W.W. Norton & Company, New York, NY.

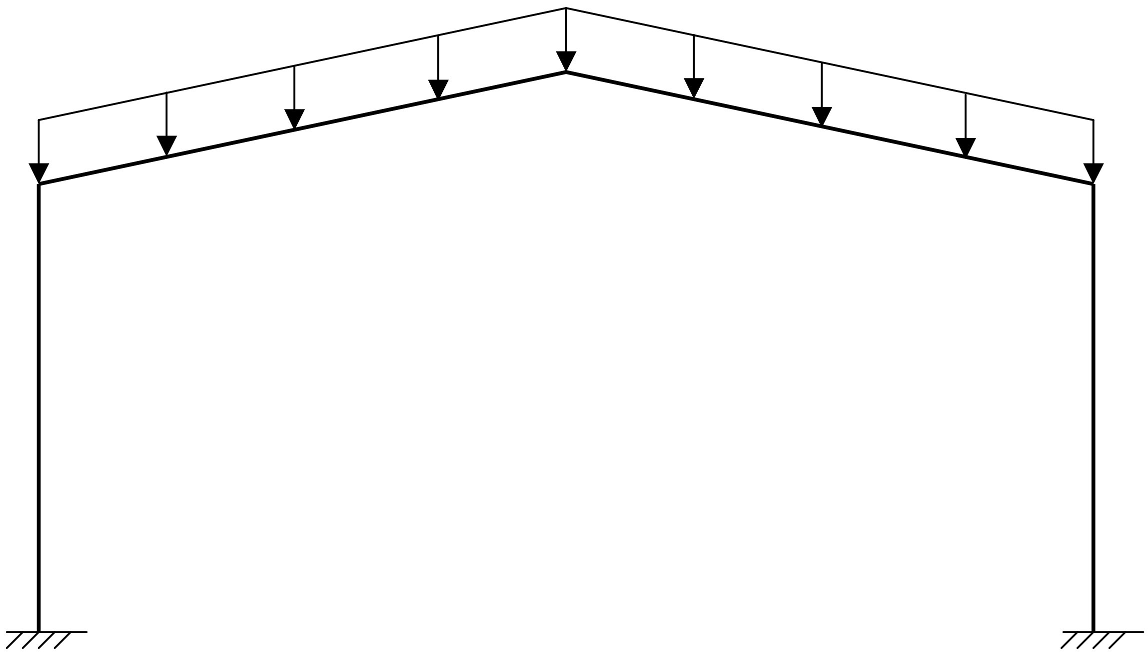

Figure 1a

Fixed-base Portal Frame

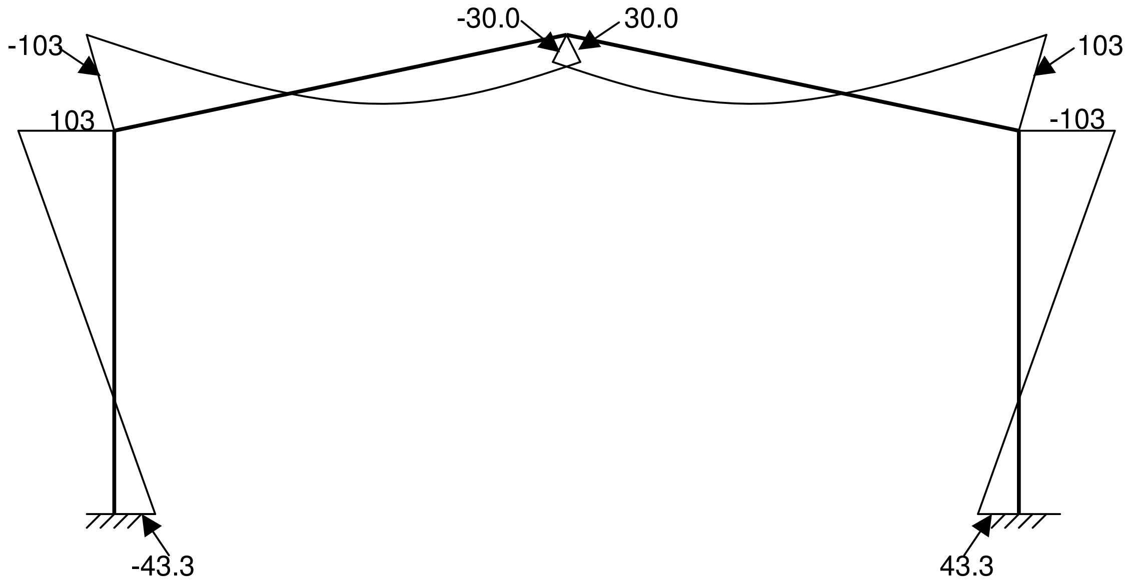

Figure 1b

Bending Moment Analysis of Fixed-base Portal Frame

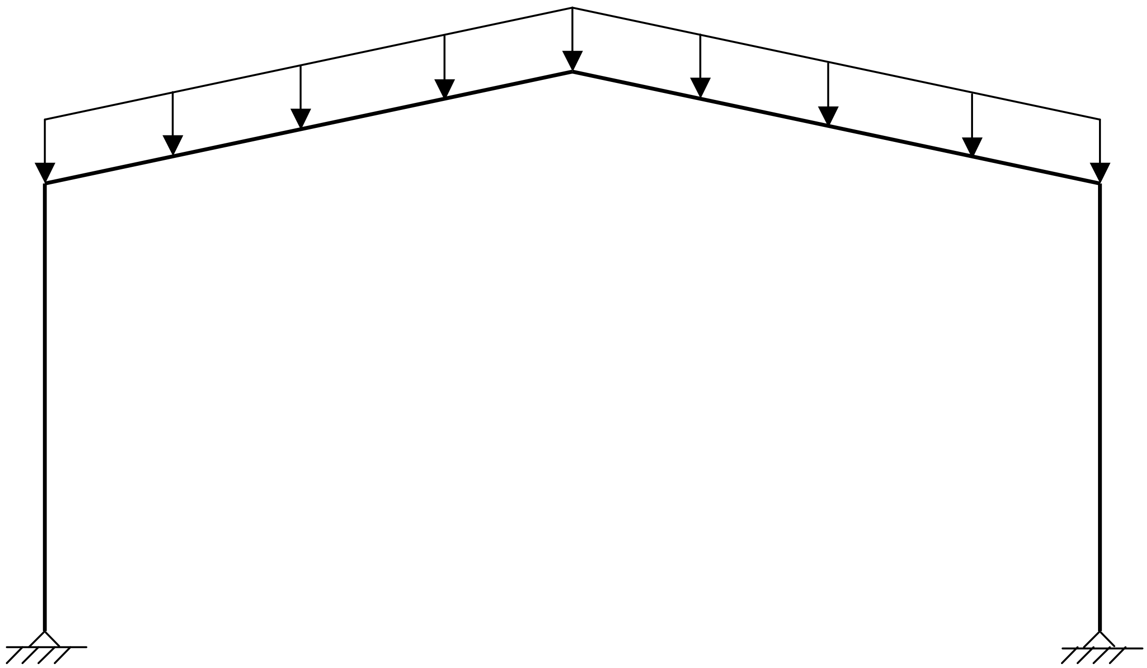

Figure 1c

Pinned-base Portal Frame

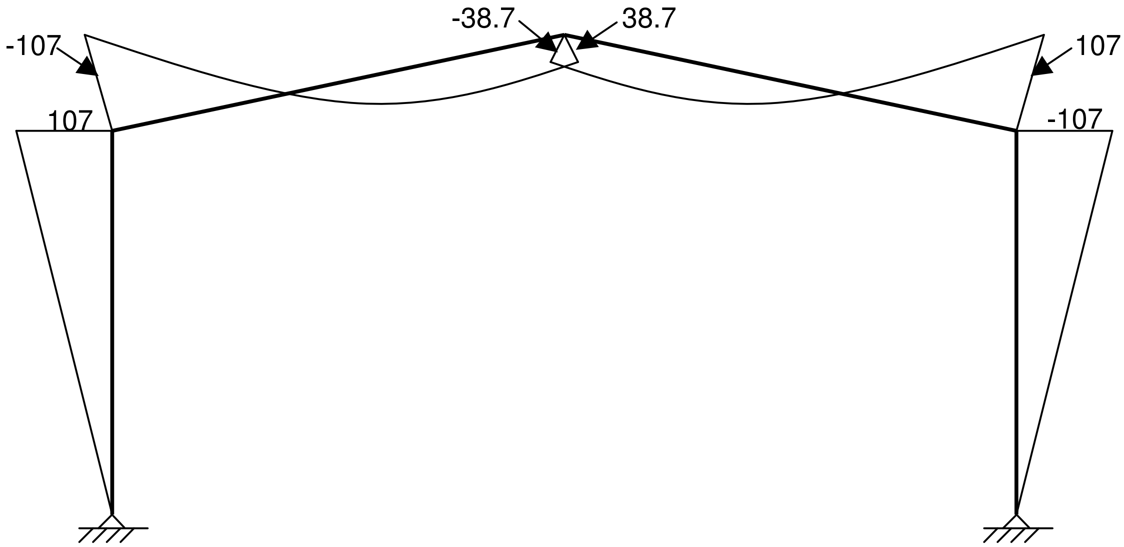

Figure 1d

Bending Moment Analysis of Pinned-base Portal Frame

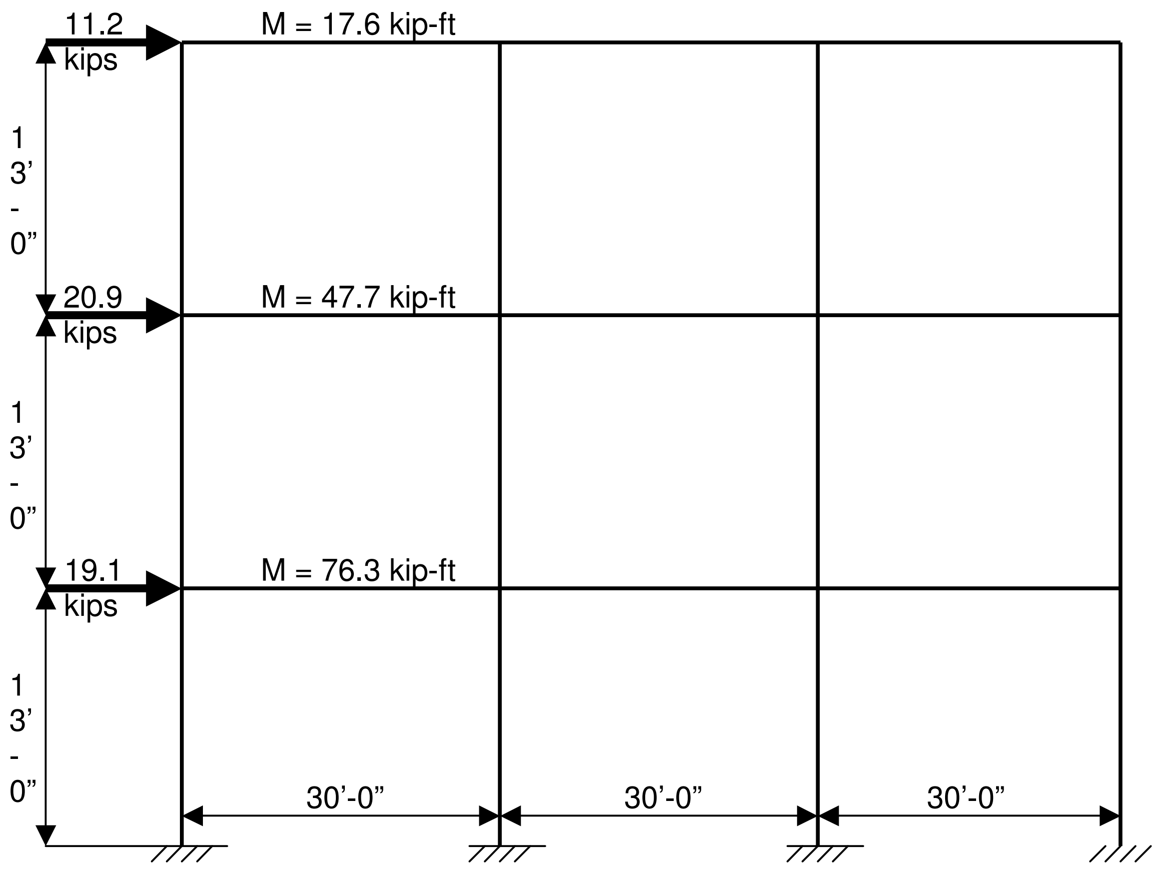

Figure 2a

Exact Frame Analysis Solution

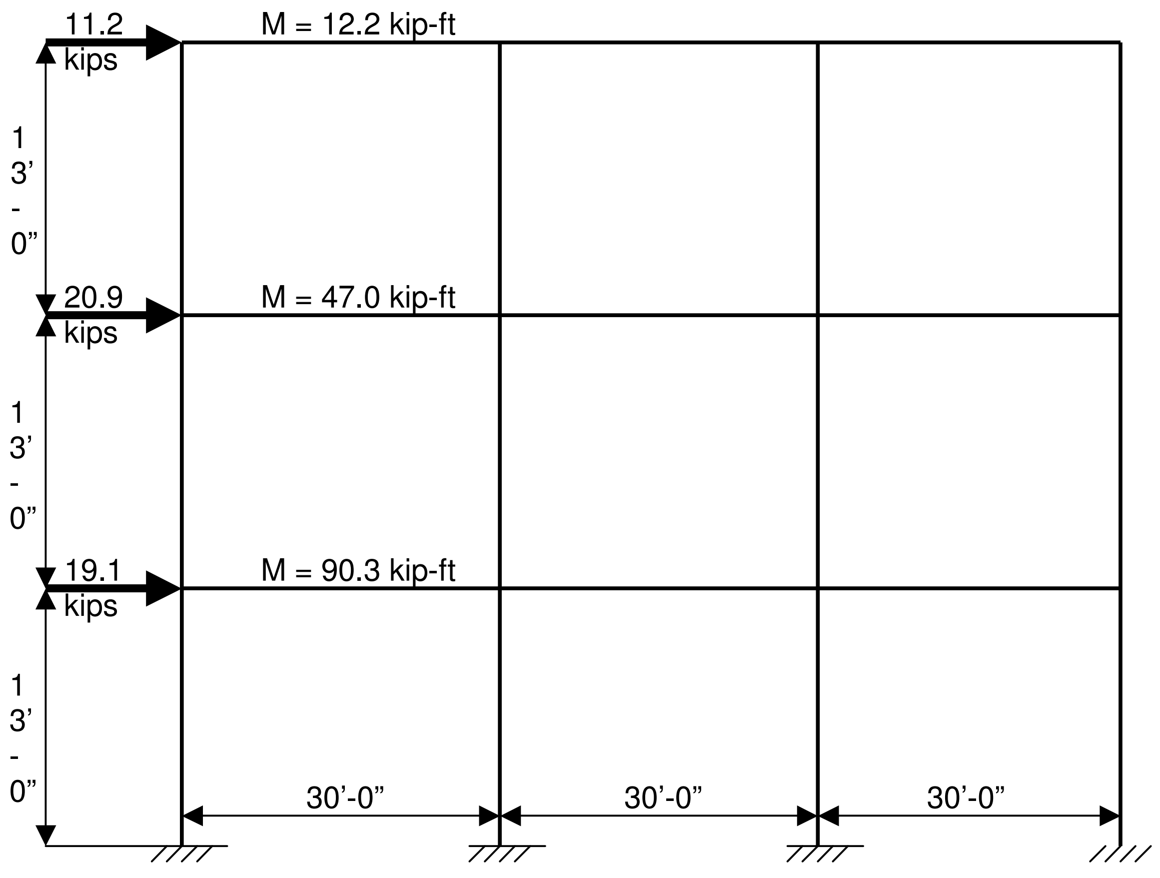

Figure 2b

Approximate Frame Analysis Solution

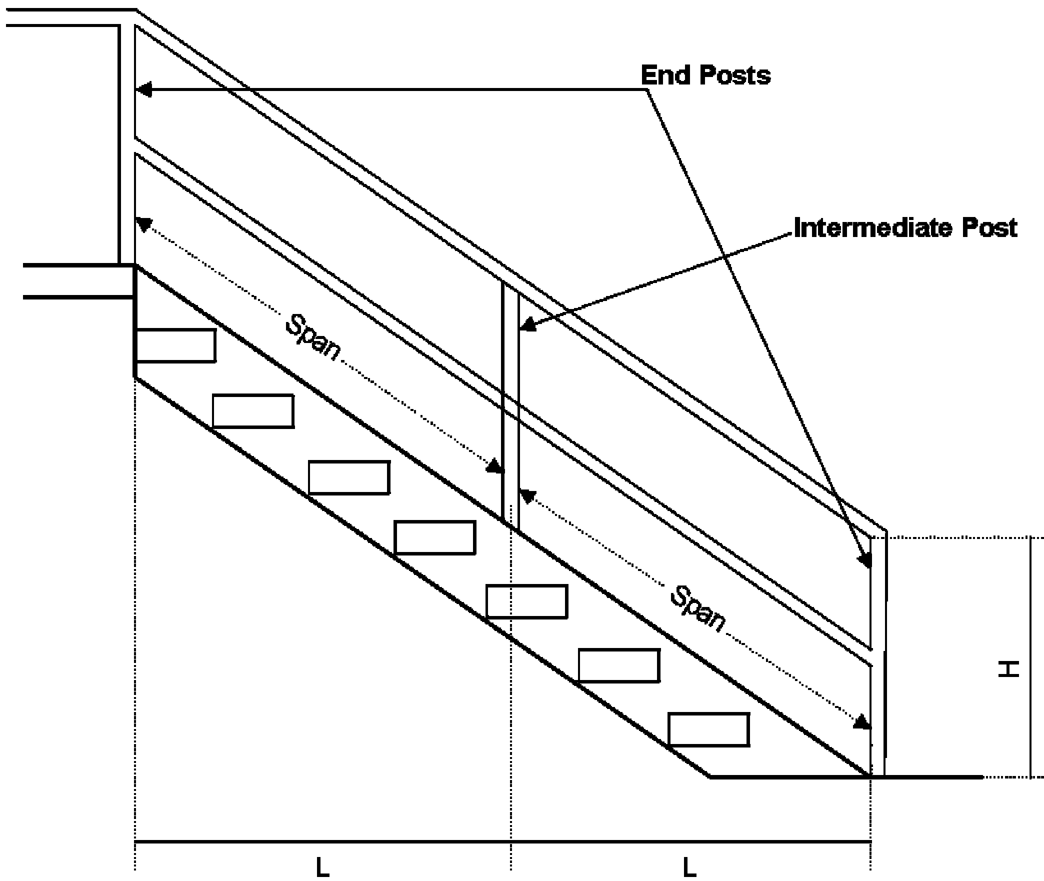

Figure 3

Guardrail Design

QUIZ

Justifiable Precision and Accuracy in Structural and Civil Engineering Calculations

1. Until the mid-1970's, an engineer using a slide rule could report an answer to ____________________ significant figures.

   a. One or two
   b. Two or three
   c. Three or four
   d. Five or six

2. The quality of being exactly or sharply defined or stated is:

   a. Accuracy
   b. Precision
   c. Error
   d. None of the above

3. The quality of freedom from mistake or error:

   a. Accuracy
   b. Precision
   c. Error
   d. None of the above

4. Per ASTM E29, the rule when multiplying or dividing is that the result shall contain _____________ significant digits than the value with the smaller number of significant digits.

   a. More
   b. Less than
   c. Two times
   d. No more

5. In structural design calculations, the Load Effect should be ____________ than the Structural Resistance.

   a. Greater than
   b. Greater than or equal to
   c. Less than
   d. Less than or equal to

6. The dead load on a structure can be predicted with _______________ certainty than the transient live load.

a. Greater
b. Less
c. Equal
d. Indeterminate

7. Design live loads determined using ASCE 7 can be determined to how many significant figures?

a. One or two
b. Two or three
c. Three or four
d. Five or six

8. Load combinations can be determined to how many significant figures?

a. One or two
b. Two or three
c. Three or four
d. Five or six

9. For practical structural calculation applications, the maximum number of significant figures that should be reported is:

a. 1
b. 3
c. 5
d. 7

10. The design strength of reinforced concrete should not be reported to a level of precision greater than ________ significant figures

a. 1
b. 2
c. 3
d. 4