The Evolution of Structural Design Specifications in the United States

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Much has been written over many years concerning the development of the Load and Resistance Factor Design (LRFD) methodology used for structural design in the United States, yet many practicing engineers have had minimal exposure to how LRFD evolved from the Allowable Stress Design (ASD) methodology. This article is a simplified synopsis of that evolution and concludes with an assessment of its consequences.

ASD for Structures

Prior to the advent of the means for structural analysis, element sizing was based on force and failure capacity – if some element failed, it was simply replaced with a larger element. One could consider this a strength methodology.

When measuring internal stresses became possible, engineers developed interest in understanding elastic methods of analysis with its accompanying determination of stresses. The sizing of elements was then based on the comparison of predicted stresses in a structural element to an assumed failure stress of the element divided by a factor of safety. This philosophy was used for the three most common construction materials: concrete, metal and wood. The determination of failure stresses and appropriate factors of safety were unique to each material, but were all developed using similar approaches. Due to the unique characteristics of wood, this article will focus on concrete and steel elements.

The sizing of elements was based on groupings of different loads – self-weight (i.e., dead load), live load (e.g., vehicular loading), wind load, etc. – and considered a probability of occurrence dependent on the grouping. In the case of a bridge structure, an element might have been sized for a group load of dead plus live load compared to 100% of the allowable stress. The element may also have been checked for stresses caused by a combination of dead plus wind load at 125% of the allowable stress. Elements of building structures were sized similarly in accordance with the loads acting thereon. Although this design philosophy had recognized deficiencies and weaknesses, it served well and was employed late into the twentieth century.

LRFD for Buildings

A simplistic explanation of the cause for the next step in design methodology was the massive damage to buildings and bridges in Europe during both World Wars. Material shortages led European engineers to use material more efficiently in the design of replacement structures. Because concrete was more readily available than steel, the first material specification to evolve was that for concrete, and the first portion of the construction industry to be affected was that for buildings, represented today by the American Concrete Institute (ACI) in the United States.

Research in the 1930s and 1940s led to the development of a new design methodology termed Ultimate Strength Design, named in part because concrete does not behave in a linear elastic manner. There were two major modifications from the ASD methodology. The first addressed the grouping of multiple types of loads, each having its own load duration, timing and potential for overload. Different factors were incorporated for each type of load. More predictable loads (e.g., dead load) have a lower load factor, while more variable loads (e.g., live, wind or snow) have a higher load factor. The second modification introduced a "resistance" or "capacity reduction" factor to downgrade the theoretical (nominal) capacity of an element to account for variation in material, analysis/design assumptions and equations, fabrication, and erection. While these modifications could have continued with a comparison of stresses, this new methodology changed to a comparison of strengths.

The 1963 edition of ACI's *Building Code Requirements for Reinforced Concrete* prompted a rapid transition from Working Stress Design to Ultimate Strength Design. ACI introduced the "Strength Method" in its 1971 edition, while identifying Working Stress as an "alternate method." While still identified as the "Strength Method," this methodology is generally equivalent to today's popular generic reference to LRFD.

The steel buildings industry followed a similar but slightly delayed path. The American Institute of Steel Construction (AISC) first published its *Standard Specification for Structural Steel for Buildings* in 1923, based on the allowable stress methodology. While ultimate strength methodology had been considered for quite some time, AISC delayed its adoption until much later in the twentieth century. By the time it did so, its popular naming convention had changed. It was not until 1986 that AISC published its first *Load and Resistance Factor Design Specification for Structural Steel Buildings*. The 2005 edition unified the provisions presented in the 1989 *Specification for Structural Steel Buildings: Allowable Stress Design and Plastic Design* and the 1999 *Load and Resistance Factor Design Specification for Structural Steel Buildings*.

LRFD for Bridges

The American Association of State Highway and Transportation Officials (AASHTO) governs bridge design in the United States. While the industry generally uses research and specifications developed by ACI for concrete elements and AISC for steel elements, AASHTO traditionally has recognized that bridges should be designed somewhat differently than buildings. Bridges are subject to more rigorous and aggressive environmental effects, and their live loading is typically more variable than that of buildings. Accordingly, in general terms, bridge design necessitates larger factors of safety and higher capacity reduction factors.

The first national highway bridge specifications were published in 1931, based on ASD methodology. Unlike ACI and AISC building specifications, bridge specifications had an interim step in their transition from ASD to LRFD. AASHTO adopted "Load Factor Design" (LFD) in 1973 for concrete and steel elements. LFD incorporated the concept of variability of individual loads and based the sizing of elements on strength rather than stresses. AASHTO still accepted ASD methodology for bridge design in its *Standard Specifications for Highway Bridges* until the 17th edition in 2002. Through extensive effort in the late 1980s and early 1990s, AASHTO developed and adopted LRFD for bridge design with its first publication in 1994. From 1994 until the final edition of the *Standard Specifications* in 2002, LRFD was promoted as the intended replacement methodology. AASHTO no longer updates provisions for design using ASD methodology. Similar to AISC's LRFD provisions or ACI's strength provisions, AASHTO's LRFD includes both factored loads and resistance factor reductions in nominal capacity. The adoption of LRFD in bridge specifications required a significant effort to update provisions for live loading and relied on the extensive use of statistical methods.

Consequences of the ASD to LRFD Evolution

These changes in design methodology were evolving as computers steadily became more available, allowing for more efficient and refined evaluations and design. Separate from the element capacity aspects of design specifications, the governing codes for loads have also become much more refined and comprehensive. Using modern specifications and codes, it is impractical to design structures (buildings or bridges) without software. The extreme refinement of loading and proliferation of load combinations has expanded to an excessive degree, as if it is desirable and possible for results to reflect reality precisely.

In light of the ever-increasing pressure to design larger and more complex structures, one might be inclined to advocate for the most comprehensive and sophisticated specifications and codes. However, the vast majority of structures are still relatively small. Current complicated and involved specifications and codes make it more difficult for less experienced designers to judge whether the results make sense or where they may be suspect.

Given that the "ship has sailed" regarding the evolution of design specifications, it is incumbent on senior staff to mentor those with less experience, so that they consider carefully the assumptions made in computer modeling and use alternative methods to determine if element sizing is appropriate. Now and in the future, it is also incumbent on those actively engaged in the design of structures to take an increased interest in proposed additional modifications and refinements of codes and specifications, in order to ensure that engineering remains a true profession and does not turn into a fully mechanized service industry.■
