Empirical Design in Structural Engineering

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Thomas Boothby

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To my students and teachers

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About the author

Thomas Boothby is Professor of Architectural Engineering at the Pennsylvania State University. He has over 40 years of experience in structural engineering, including 10 years as a structural designer. He has a significant record of publications on the structural interpretation of medieval architecture, the analysis and assessment of masonry and iron bridges, and the application of fibre-reinforced polymers to structural engineering. He is the author of *Engineering Iron and Stone: Understanding Structural Analysis and Design Methods of the Late 19th Century* and *Empirical Design for Architects, Engineers, and Builders*. He is a registered architect and professional engineer and a Fellow and Life Member of the American Society of Civil Engineers.

Preface

This book is a reflection of an outlook I have developed throughout my career, during the 1980s as a design engineer, and later as an academic engineer. I realised at an early stage that an engineer's work involved more than the application of science to problems of construction. An engineer's activity requires the application of experience, which could supplement, replace, or even overrule the results of a rational understanding of structures. In my career as an academic engineer, I spent a large part of my time reviewing the design of unreinforced masonry structures: nineteenth century masonry bridges and gothic or neo-gothic architecture. As structures whose conception was based on experience, these works speak eloquently about the success of empirical design. In fact, much of the contemporary research on these structures attempts to use rational analysis procedures to understand what their builders understood very well empirically. So, while developing an understanding of the successes of empirical design, I started applying empirical design to modern structures and investigating the empirical content of the modern practice of structural engineering. I found that empirical design was a very useful method for teaching engineers and architects to look first at the design of the whole structure and then apply their detailed methods to the elements of the structure. In a previous book, *Empirical Structural Design for Architects, Engineers, and Builders*, I describe systematically how this method can be applied to determining the configuration, materials and sizes of the elements of a structure – the intent of this book was to teach the application of these methods.

Within the past ten years, I have discovered empiricist philosophy and have learned that it can be applied to an understanding of empirical design. The central idea of this school of philosophy is that experience, rather than reason, is the way that we learn about the world. This is also the idea of empiricist design, that design based on prior experience is at least as effective as design based on a scientist's understanding of the world. These investigations have shaped my outlook that structural engineering does not depend wholly on science or reason. Structural engineering is a collection of empirical procedures sometimes informed by science.

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Chapter 1
Empirical design in structural engineering

1.1. Introduction

Empirical design is design by experience that is applied by using past successes directly as a basis for later designs. The experience may be direct personal experience on the part of the designer, or it may be collective experience of previous designers, often distilled into simple rules. Empirical design is an effective means of establishing the initial premises of a design and determining materials, configuration, size and spacing of the components of a structural design. The effectiveness of empirical design is simply that it is using proved procedures to achieve a favourable result in the design of a building structure: a structure that achieves the purpose of resisting applied loads, is an effective complement to the architecture of the building and is of reasonable dimensions.

Empirical design was the only means of completing a building design to the beginning of the nineteenth century and the more effective means during the nineteenth century, so the production of successful buildings predates the appearance of rational design by approximately two millennia. Figure 1.1 illustrates two structures whose design was wholly or partially empirical.

Figure 1.1 View of Amiens, France

Even with the analytical methods available to contemporary engineers, empirical design is commonly used in engineering in two basic circumstances: first, where a product design has become so routine that further detailed design is no longer necessary, and the second where the application of analytical rules is too complicated to apply in routine design.

A house carpenter who sizes rafters, joists, beams and studs in the framing of a house simply by knowledge of what size is required for a given span is practising empirical design. So is an engineer who sizes small lintels in a brick wall with the depth equal to 1/12 of the span, or an engineer who recognises that 90 mm steel angles are suitable as lintels because their legs are approximately the width of a brick and because they can span up to 1800 mm based on a span: depth ratio of 20. Empirical design may be thought to be obsolete in an age in which we are able to calculate the stresses resulting from structural loads and calculate the resistance of the members that resist these loads. However, the remainder of the book will describe the continuing utility of empirical design.

Empirical design is necessary for the establishment of minimum or standard values of the size, materials and configuration of structural elements. The experience with failures of members and connections is often necessary to be able to identify a minimum size or quantity of a structural element. As an example, where the calculated forces in a bolted steel connection may allow the use of 6 mm dia. bolts, a minimum of 12 mm or 14 mm diameter would be observed by most professionals, because a smaller bolt may be subject to failure by unpredicted effects. Similarly, unwritten standards often prevail in the design of other elements of a structure. In the US, 115 mm thick normal weight concrete floor slab is effectively a standard practice, because experience dictates that this is the minimum thickness necessary for fire protection.

Empirical design is useful for the design of elements that are too complex to calculate. Connections furnish many examples of this application of empirical design. It is difficult (and certainly not worth the trouble) to calculate the force acting on a single nail on a plywood sheathing panel subjected to wind loads. The spatial and temporal variations of wind pressure on a cladding panel are very difficult to capture analytically. Similarly, the nails around the perimeter of a sheet of plywood have differing resistances and differing stiffnesses, so that the distribution of forces to the nails is further complicated. The actual resistance of a single nail is also a quantity that is variable depending on the density of the wood, the straightness of the nail and other unknown factors. As a result of these uncertainties, we rely on tables to furnish us with an empirically determined nominal resistance of the nail under defined conditions. Figure 1.2 is an excerpt from the special provisions for design for wind and seismic forces (AWC, 2021) that accompanies the National Design Specification (AWC, 2018) for wood structures in the US, which illustrates the design of wood panel products under the uncertainties of loading and resistance of these connections. Pull-out forces on an anchor bolt in a concrete spread footing furnish a similar example. These are instances of a more general principle that we resort to empirical design when the stresses become too difficult to calculate, or too unpredictable, being based on many other factors.

Empirical design is embedded in modern building codes. As one example, the US steel design code (AISC, 2016) develops rules for the analysis of partially composite steel–concrete beams. For fully composite beams, the rules are a straightforward application of the theory of plasticity

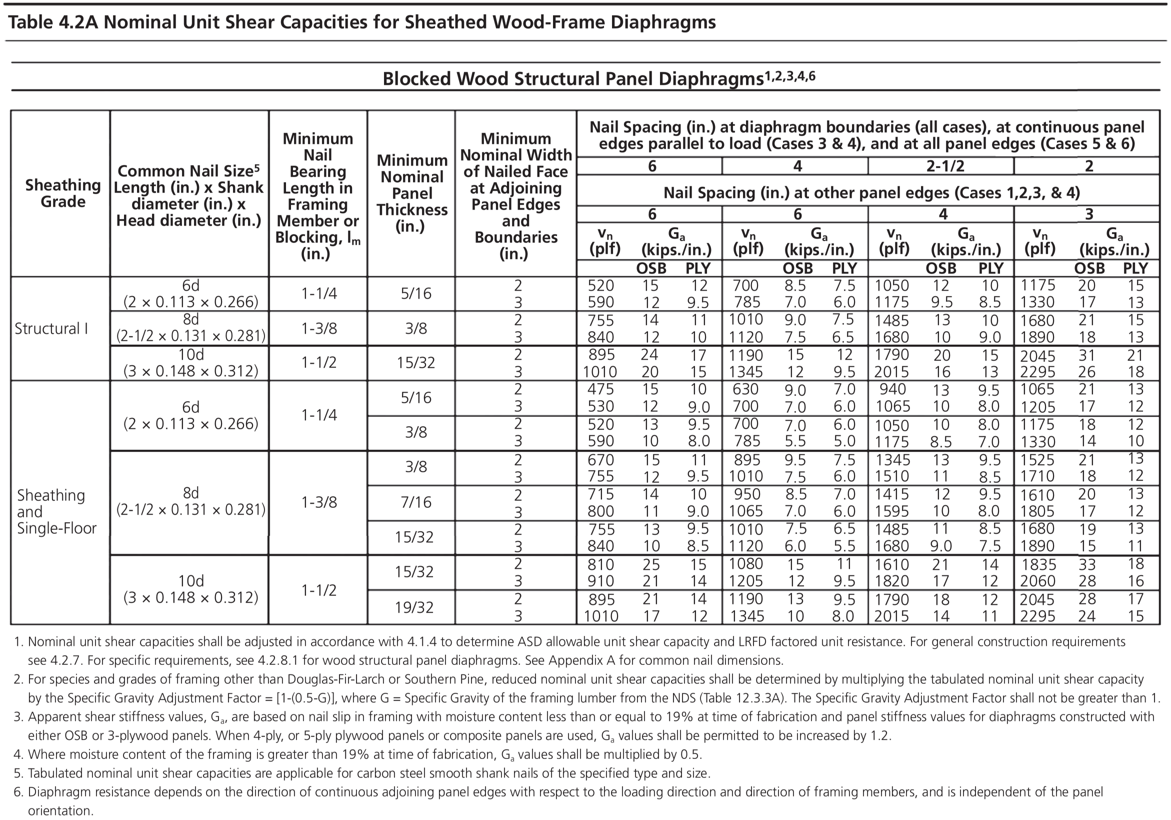

Figure 1.2 Analysis of plywood fastening (AWC, 2021). Courtesy of American Wood Council, Leesburg, VA

Table 4.2A Nominal Unit Shear Capacities for Sheathed Wood-Frame Diaphragms

Blocked Wood Structural Panel Diaphragms[1,2,3,4,6]

Sheathing Grade	Common Nail Size[5] Length (in.) x Shank diameter (in.) x Head diameter (in.)	Minimum Nail Bearing Length in Framing Member or Blocking, l_m (in.)	Minimum Nominal Panel Thickness (in.)	Minimum Nominal Width of Nailed Face at Adjoining Panel Edges and Boundaries (in.)	Nail Spacing (in.) at diaphragm boundaries (all cases), at continuous panel edges parallel to load (Cases 3 & 4), and at all panel edges (Cases 5 & 6)											
					6			4			2-1/2			2		
					Nail Spacing (in.) at other panel edges (Cases 1,2,3, & 4)											
					6			6			4			3		
					v_n (plf)	G_a (kips./in.)		v_n (plf)	G_a (kips./in.)		v_n (plf)	G_a (kips./in.)		v_n (plf)	G_a (kips./in.)	
						OSB	PLY		OSB	PLY		OSB	PLY		OSB	PLY
Structural I	6d (2 × 0.113 × 0.266)	1-1/4	5/16	2	520	15	12	700	8.5	7.5	1050	12	10	1175	20	15
				3	590	12	9.5	785	7.0	6.0	1175	9.5	8.5	1330	17	13
	8d (2-1/2 × 0.131 × 0.281)	1-3/8	3/8	2	755	14	11	1010	9.0	7.5	1485	13	10	1680	21	15
				3	840	12	10	1120	7.5	6.5	1680	10	9.0	1890	18	13
	10d (3 × 0.148 × 0.312)	1-1/2	15/32	2	895	24	17	1190	15	12	1790	20	15	2045	31	21
				3	1010	20	15	1345	12	9.5	2015	16	13	2295	26	18
Sheathing and Single-Floor	6d (2 × 0.113 × 0.266)	1-1/4	5/16	2	475	15	10	630	9.0	7.0	940	13	9.5	1065	21	13
				3	530	12	9.0	700	7.0	6.0	1065	10	8.0	1205	17	12
			3/8	2	520	13	9.5	700	7.0	6.0	1050	10	8.0	1175	18	12
				3	590	10	8.0	785	5.5	5.0	1175	8.5	7.0	1330	14	10
	8d (2-1/2 × 0.131 × 0.281)	1-3/8	3/8	2	670	15	11	895	9.5	7.5	1345	13	9.5	1525	21	13
				3	755	12	9.5	1010	7.5	6.0	1510	11	8.5	1710	18	12
			7/16	2	715	14	10	950	8.5	7.0	1415	12	9.5	1610	20	13
				3	800	11	9.0	1065	7.0	6.0	1595	10	8.0	1805	17	12
			15/32	2	755	13	9.5	1010	7.5	6.5	1485	11	8.5	1680	19	13
				3	840	10	8.5	1120	6.0	5.5	1680	9.0	7.5	1890	15	11
	10d (3 × 0.148 × 0.312)	1-1/2	15/32	2	810	25	15	1080	15	11	1610	21	14	1835	33	18
				3	910	21	14	1205	12	9.5	1820	17	12	2060	28	16
			19/32	2	895	21	14	1190	13	9.5	1790	18	12	2045	28	17
				3	1010	17	12	1345	10	8.0	2015	14	11	2295	24	15

1. Nominal unit shear capacities shall be adjusted in accordance with 4.1.4 to determine ASD allowable unit shear capacity and LRFD factored unit resistance. For general construction requirements see 4.2.7. For specific requirements, see 4.2.8.1 for wood structural panel diaphragms. See Appendix A for common nail dimensions.
2. For species and grades of framing other than Douglas-Fir-Larch or Southern Pine, reduced nominal unit shear capacities shall be determined by multiplying the tabulated nominal unit shear capacity by the Specific Gravity Adjustment Factor = [1-(0.5-G)], where G = Specific Gravity of the framing lumber from the NDS (Table 12.3.3A). The Specific Gravity Adjustment Factor shall not be greater than 1.
3. Apparent shear stiffness values, G_a, are based on nail slip in framing with moisture content less than or equal to 19% at time of fabrication and panel stiffness values for diaphragms constructed with either OSB or 3-plywood panels. When 4-ply, or 5-ply plywood panels or composite panels are used, G_a values shall be permitted to be increased by 1.2.
4. Where moisture content of the framing is greater than 19% at time of fabrication, G_a values shall be multiplied by 0.5.
5. Tabulated nominal unit shear capacities are applicable for carbon steel smooth shank nails of the specified type and size.
6. Diaphragm resistance depends on the direction of continuous adjoining panel edges with respect to the loading direction and direction of framing members, and is independent of the panel orientation.

to flexural members. However, for the calculation of deflections in partially composite beams, the code resorts to the calculation of empirical lower bounds on the deflection.

All the building and material codes that prescribe the design of connections have significant empirical content. Connections in wood structures depend on a variety of fastener capacities that are given in a table, which has been developed based on a limited number of tests. Design values for steel bolts are subject to primarily empirical modifications for the size of the hole, the edge and end distance of the hole and other factors. As an example from the Eurocodes, Eurocode 5 contains a procedure for addressing the highly statically indeterminate distribution of shear forces in a multi-member wood connection, by simply considering statically each potential shear plane (Porteous, 2013, paragraph 8.1.3).

The application of new structural materials develops empirically. Reinforced concrete, when this material first appeared in the nineteenth century, had no analytical procedure for ensuring the strength and safety of a structure built with this material. Early versions of a design procedure for this material relied in part on proportional rules, and in part on a rudimentary, intuitive view of the behaviour of a reinforced concrete structure. This outlook has been described by Boothby and Clough (2017) and will be elaborated in Chapter 3.

Empirical design is an effective tool for completing the initial design of a building. The following cases represent examples of this application of empirical design.

A structural engineer may be required to deliver a preliminary design to an architect for elaboration before they have had the opportunity to size the structure completely or to determine the extent of the reinforcement.

In order to obtain tenders for an accelerated project, an engineer designs the dimensions of the frame in steel or concrete without specifying exactly the sizes, spacing and configuration of the concrete reinforcement. In particular, for a reinforced concrete structure, the sizes of the slabs, joists, beams and columns may be prescribed along with an allowance for the volume of the reinforcement. This allows the project to be estimated and bid, based on dimensions of concrete structure and estimated weight of reinforcement, before the specific structural design is complete. In order to know the appropriate thickness of a floor slab or dimensions of a beam or column, it is necessary to have sufficient experience to be able to choose these sizes effectively.

An architect or structural engineer who determines bay sizes appropriate to a specific structural material or system as an initial step in the structural design process is practising empirical design. Subtleties that result from experience are often part of these decisions. Such subtleties may include modifying the span of the exterior bay or the placement of the exterior columns to reflect differences in loading and resistance, or the use of slightly rectangular bays to reflect the span direction of joists or infill beams and the span of girders.

An arbitrary minimum design value for a bolted connection and an arbitrary minimum depth of a beam-column connection may be specified, again without regard for actual loading conditions. An excerpt from the notes of a structural steel construction document (Penn State

University, 2014) imposes a minimum capacity of a beam connection regardless of the actual load on the beams.

> Design connections using the 'maximum total uniform load' tables in the AISC manual. For non-composite beams, the connection capacity shall be at least 50% of the maximum total uniform load, for composite beams, the connection capacity shall be at least 80% of the maximum total uniform load.

In contemporary engineering practice, the successful application of optimisation to engineering design problems requires the insertion of a credible initial estimate, known as the seed, to ensure that the optimisation routine converges on a practical solution. Most ordinary design techniques are iterative, but iterative processes are more expedient if there is a reasonable starting point. Empirical design can provide a suitable initial design to be used as a starting point for optimisation.

Further and more detailed examples of the use of empirical design are discussed throughout the remainder of this book both from a general point of view and in specific applications.

Empirical design has a basis in epistemology, the philosophy of the acquisition and verification of knowledge, that lends credit to its effectiveness as a design method. Empiricism is the outlook that knowledge is assembled from experience or observation without recourse to reason, and that the application of reason does not provide useful information about the universe. A rationalist outlook is that by reasoning, even in the absence of concrete evidence, we can make significant discoveries about the functioning of materials or of natural processes. Although empiricists understand mathematics and find it interesting, they doubt that mathematical manipulations tell us anything useful. An example of this, which will be discussed later, is the Euler formula for the buckling of an elastic column. This is an elegant mathematical theory that some empirically minded engineers have dismissed as not useful for evaluating the columns in real buildings because these columns are not slender enough for the formula to be applicable. In fact, even the building codes that acknowledge the merit of this formula use an empirically determined means of constructing the curve within the range of columns of practical interest.

An examination of the history of building will show that concepts from natural science were not directly applied to the understanding of building systems until the nineteenth century. Up to that time, the sizes of structural elements were based on experience, usually transmitted through some sort of proportional rules. The creation of usable, enduring structures by ancient building methods, which were exclusively empirical, speaks to the potential success of empirical design in similarly creating usable and enduring structures. On the other hand, a very modern outlook on engineering, the idea of data-driven design, or data-driven artificial intelligence, uses empirical information to achieve a design result without recourse to a physics-based model.

The application of empirical design in practice requires the consideration of the ethics of using a method only indirectly endorsed by the building profession. The ethical dimensions of empirical design are considered in a later chapter. The fundamental ethical question is to what extent an engineer may choose to base their decisions on empirical engineering. This question is closely connected to the discussion of building codes and empirical design. The premise of most of the building codes is that design of structures should follow rational principles. However, there are occasions when rational design is simply not possible. In cases like this, it may be necessary to consider experience and to act accordingly. There are other cases in which resorting to experience and trusting calculations are two alternative pathways to arriving at a competent design. In these cases, there is considerable pressure on an engineer to follow the practice of presenting calculations according to the requirements of a building code. There is merit to completing an empirical design in parallel, and using the two designs, empirical and rational, as a means of checking the other. In the end, it may be argued it is ethical to use a design method that has been proved over 20 centuries.

The following is a chapter-by-chapter summary of the remainder of the book.

Chapter 2 describes the philosophical basis of empirical design, primarily from the point of view of epistemology, the branch of philosophy that deals with the acquisition and validation of knowledge.

Chapter 3 outlines a more practical view of empiricist philosophy, relating it to works on the philosophy of engineering.

Chapter 4 examines the methods used by empirical builders throughout the past two millennia and these builders' successes that can be attributed to empirical design.

Chapter 5 discusses how contemporary building codes and contemporary engineering practice may be more conventionalist and empiricist and less rational.

Chapter 6 examines the ethical issues in using empirical design in contemporary engineering practice.

Chapters 7–10 are case studies in the application of empirical design, from the point of view of a twenty-first century engineer.

Chapter 7: preservation engineering
Chapter 8: forensic engineering
Chapter 9: wood-framed building superstructure
Chapter 10: foundation design

Chapter 11 looks at further potential uses of engineering design, including the use of empirical design in artificial intelligence and optimisation applications.

Chapter 12 presents conclusions based on the information from the previous chapters.

1.2. Conclusions

The premise of the following book, then, is that design by experience has a long history of effective application to the design of buildings and can continue to be used, consciously or unconsciously, by contemporary engineers. Earlier chapters will be an investigation into empiricism and the engineering implications of empiricism, the philosophical basis of empirical design. These investigations will be undertaken to understand how an understanding of the processes of nature can lead engineers to understanding the authority of experience. The following chapters will describe how contemporary building codes have embedded empirical content, through an analysis of portions of contemporary building codes, such as the Eurocodes and the ASCE 7 code for structural loading in the USA.

The ways in which empirical design can be effectively used are in the assessment of historic structures, the design of foundations, the completion of routine or repetitive designs, or in the application to structures whose analysis is overwhelmingly complex. In the latter case, empirical design may be used in its traditional form or may be implemented by computer methods, including data-driven methods or artificial intelligence.

Empirical design has further value as a way of determining approximate configurations, materials and sizes of structural elements for buildings. There are situations in which this is a necessity for practising engineers, such as fast-track construction, or for developing documents for tenders in a reinforced concrete building when the exact design of the reinforcing steel is not available.

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