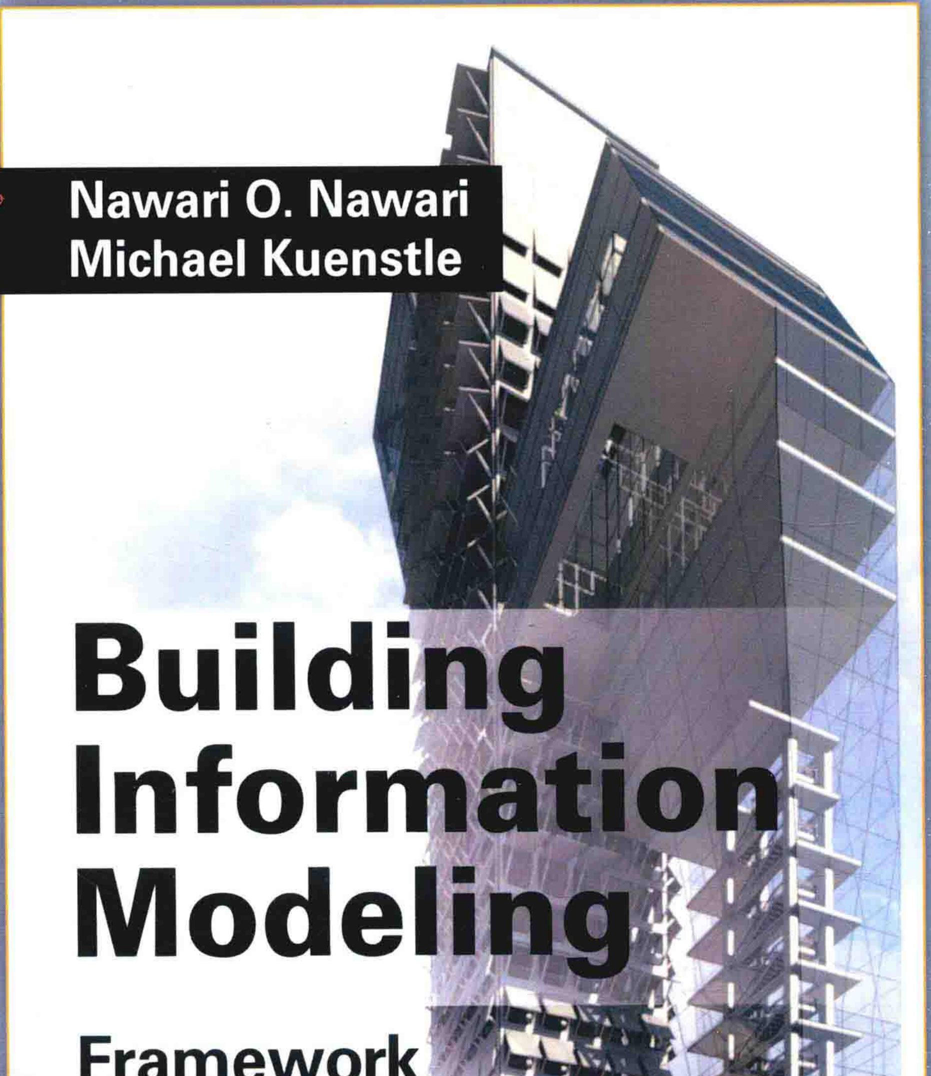

Nawari O. Nawari
Michael Kuenstle

Building Information Modeling

Framework for Structural Design

CRC Press
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Preface

This is a book primarily about building information modeling (BIM) technology and its application in the structural analysis and design of building structures. The material is presented using relevant case study BIM projects and provides example modeling techniques and exercise problems with solutions. An underlying goal for the material covered is to present the use of BIM technology as part of a design process or BIM framework that can lead to a more comprehensive, intelligent, and integrated building design—a design by which an optimized structural solution can be achieved in harmony with a building's intrinsic architectural concepts and spatial purpose. With this unique emphasis on the application of BIM technology for exploring the intimate relationship between structural engineering and architectural design, the material presented is well suited for students of engineering, architecture, and construction management and can also serve as a valuable resource for building design professionals, building contractors, subcontractors, and fabricators.

The book includes a discussion of current and emerging trends in structural engineering practice and the role of the structural engineer in building design using new BIM technologies. This new technology is significantly transforming twenty-first-century practice activities and is emerging as one of the most promising advances in the architecture, engineering, and construction (AEC) disciplines. Presently, the AEC industry continues to inform its association members and stakeholders about BIM adoption in a variety of ways, including this book. However, at the very core of the BIM evolution is education.

The BIM framework for structural design proposed and presented in this book provides a method to explore a structural design by blending various threads of knowledge that can inform a given building structure; some may seem contradictory and incompatible to arrive at structural beauty and correctness. This BIM framework is referred to as the *structure and architecture synergy framework* (SAS framework) or as the *buildoid framework* (students' preferred name). The SAS framework facilitates for the exploration of a structural design as an art while emphasizing engineering principles and thereby provides an enhanced understanding of the influence structure can play in form generation and defining spatial order and composition. The proposed SAS framework will allow architects and engineers to applaud the fusion of art and science and cultivate professional qualities to meet the demands of today's as well as tomorrow's integrated practice requirements.

This key relationship between structure and architecture is therefore fundamental to the art of building. It sets up conflicts between the technical, scientific, and artistic agendas that architects and engineers must resolve. The method in which the resolution is carried out is one of the most critical criteria for the success of a building design. The SAS framework focuses on the resolution of such conflict by enhancing the understanding of the interplay between architecture and structure as well as expanding the design vocabulary.

About the Authors

Dr. Nawari (Ph.D., P.E., M.ASCE) has more than 20 years of experience in design, teaching and research specializing in building structures and building information modeling. Currently, he teaches graduate and undergraduate courses at the University of Florida. He has written and co-authored over 70 publications and three books. He is an active member of the U.S. National Building Information Modeling Standard Committee (NBIMS), BIM Committee of the Structural Engineering Institute (SEI), and co-chair of the subcommittee on BIM in education and many other professional and technical societies. With significant design and build experience, Dr. Nawari is a board certified professional engineer in the states of Florida and Ohio.

Dr. Nawari received a 2014-2015 Fulbright U.S. Scholar grant for teaching and research in Kuwait. He conducted research and taught in Kuwait for ten months during fall 2014 and spring 2015. The project has an 80% teaching part and a 20% research component.

Michael W. Kuenstle, AIA, received his Graduate Architecture degree from Columbia University in New York City where he graduated with honors for excellence in design and was awarded the William Kinne Fellows Memorial Fellowship for post-graduate research. He holds a Bachelor of Architecture degree from the University of Houston where he graduated with honors for his design thesis project. Prior to attending Columbia University, he worked as a research assistant at the Chicago Institute for Architecture and Urbanism. Kuenstle served as adjunct associate professor at the New York Institute of Technology from 1990 to 1993. He has been assistant and associate professor in the School of Architecture at the University of Florida since 1993.

Over the past 20 years, Michael Kuenstle's wide range of accomplishments as an educator include developing and teaching innovative architecture design studio courses at every level of the undergraduate and graduate curriculum, advancing and implementing new building structures courses as well as technology seminars that integrate digital modeling, analysis and fabrication techniques as essential learning tools in an evolving technology curriculum. He has served as principal investigator for two significant funded interdisciplinary research projects for the Florida Department of Education and is co-author of several important publications on school facilities design and construction.

Michael Kuenstle received his early professional training in the Chicago office of Skidmore, Owings and Merrill and is co-founder and principal partner in the research-based architecture firm of Clark + Kuenstle Associates, Inc. located in Gainesville, Florida. Parallel with his teaching accomplishments, his building design projects have received several AIA design awards and have been published and exhibited throughout the U.S. and Canada. He is a licensed architect and currently serves as member of the Board of Trustees to the Florida Foundation for Architecture.

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1 Introduction

GENERAL

Historically, one of the oldest architectural structures dates to 2700 BC when the step pyramid for Pharaoh Djoser was built by Imhotep, who is considered the first architect and engineer in history known by name. Pyramids were the most common major architectural structures built by ancient civilizations because the structural form of a pyramid is inherently stable and can almost be infinitely scaled linearly in size and proportion to increased loads. There is no record of any scientific or engineering knowledge employed in the construction of pyramids during that era. The physical laws that underpin structural engineering began in the third century BC, when Archimedes published his work, *On the Equilibrium of Planes*, in two volumes. He used the principles derived to calculate the areas and centers of gravity of various geometric figures, including triangles, parabolas, and half-circles. Together with Euclidean geometry, Archimedes's work on this and on calculus and geometry established much of the mathematics and scientific foundation of modern structural engineering (W. Addis, 1992; B. Addis, 2007).

At the beginning of the eighteenth century, advances in mathematics were needed to allow structural designers to apply the understanding of structures gained through the work of Galileo, Hooke, and Newton during the seventeenth century. In that period, Leonhard Euler founded much of the mathematics and many of the principal methods that allow structural engineers to model and analyze architectural structures. Specifically, in about 1750 he developed the Euler–Bernoulli beam equation with Daniel Bernoulli (1700–1782); this equation is one of the fundamental theories used in structural analysis and design. A few years later, Euler (1757) was able to create the Euler buckling formula, which significantly advanced the ability of engineers and architects to design slender columns. His buckling equation is still one of the most fundamental equations used in various building codes to design columns and walls.

In the early nineteenth century, new construction materials, such as iron and Portland cement, played major roles in shaping the building design profession. Much of the previous century's practice tradition had to be discontinued or radically reconceptualized. This method did not fit well within the ancient norms of architecture and soon required a new type of training and education. By the middle of the nineteenth century, many engineering schools across Europe and the United States had been founded and the modern engineering profession established. Hence, there was no split between architecture and engineering; rather, a new discipline emerged alongside an older one.

From 1854 to 1872, Eugene-Emmanuel Viollet-le-Duc published important contributions to the field of architecture: the *Dictionnaire raisonne de i'architecture francaise du Xle au XVle siecle* (1854–1868) [Dictionary of French Architecture from the eleventh to the sixteenth century (1854–1868)], and the *Entretiens sur l'architecture* (1863). Their impacts were enormous, both in Europe and in America. Viollet-le-Duc became the most prominent scholar to emphasize the importance of structures in architectural design. He asked the question (Viollet-le-Duc [1854], 1990, p. 28): "On what could one establish unity in architecture, if not on the structure, that is, the means of building?" He also said: "Construction is a science; it is also an art. The practice of architecture means adapting both art and science to the nature of the materials employed."

Based on Viollet-le-Duc's principles, Pier Luigi Nervi (1965), an architect and an engineer, published his book, *Aesthetics and Technology in Building,* in which he placed his design firmly on the tradition of Viollet-le-Duc's principles, with architecture and structure inseparable. In his book, he insisted that architecture cannot be based only on pure art and explained that structure, whether large or small, must be stable and lasting, must satisfy the needs for which it was built, and must be efficient (achieving maximum results with minimum means). He indicated that these are the criteria for good architecture. He also emphasized the idea of employing the materials "according to their nature." For instance, in discussing the advantages of reinforced concrete, he stated: "Reinforced concrete beams lose the rigidity of wooden beams or of metal shapes and ask to be molded according to the line of the bending moments and the shearing stress" (as cited in Sandaker, 2008, p. 28). He asserted his views on the necessity for design to take account of the particular properties of each material and to form or adapt it to a particular shape. These views can be magnificently seen in his design of the aircraft hangers for the Italian Air Force (1940); Stadio Flaminio, Rome (1957); Palazzetto dello sport, Rome (1958); and the Cathedral of Saint Mary of the Assumption, San Francisco, California (1967).

Schueller (1995, 2007) approached the issue of the interplay between architecture and structure by emphasizing the engineering principles in architectural education alongside the application of software tools in training architects and engineers. Another viewpoint is the concept of "structural art" as described by Billington (2003). This perspective considers structural engineering as a new art form that is parallel to but independent of architecture in the same way that photography, that other new art of the nineteenth century, is parallel to but independent of painting. Billington explored structural art in the nineteenth and twentieth century specifically in Switzerland. He thoroughly reviewed the work of such Swiss structural engineers such as Wilhelm Ritter (1847–1906) and Pierre Lardy (1903–1958) and four of their students: Robert Maillart (1872–1940) and Othmar Ammann (1879–1965), who studied with Ritter; and Heinz Isler and Christian Menn, who studied with Lardy. W. Addis (1990, 1998) and B. Addis (2001) shared similar viewpoints as Billington in considering structural art as a form of art that is parallel to but independent of architecture.

In the United States, the work of Khan (2004) in the 1970s and 1980s represents a remarkable contribution to structural art and innovation because of the introduction of trussed frames and tubes, tube within tube, and bundle tubes in high-rise structural systems. Structures such as John Hancock Center, Sears Tower, and One Magnificent Mile are important milestones in the history of buildings.

Sandaker (2008) considered structures as a part of architectural context. Thus, the purpose of structure is that of not only the support function but also of spatial harmony and enclosure organization. In his view, the main purpose of the structure is to establish architectural spaces physically. It follows that the form of structures must heavily consider the spatial functions and emphasize that an understanding and appreciation of structures thus needs to be taken into account.

The proposed building information modeling (BIM) framework, which is referred to as the structure and architecture synergy framework (SAS framework) in this book, shares some views similar to those proposed by Sandaker (2008), Schueller (2007), Nervi (1965), and Viollet-le-Duc (1854, 1990); however, the SAS framework introduces an innovative design to enable the resolution of the challenges related to the conceptual linking and integration between architectural and structural engineering principles. The framework hinges on BIM and the concepts of structural melody and poetry. This new framework focuses on how to engage the student's imagination and to use it no less creatively than a musician or artist producing ideas; at the same time, it elaborates on structural analysis skills as well as on improving the ability in handling cross-disciplinary interests.

BIM IN EDUCATION

OVERVIEW

Building information modeling is a comprehensive information management and analysis technology that is becoming increasingly essential for academic education. Architecture, engineering, and construction (AEC) schools implemented a variety of pedagogical methods for introducing BIM into their curriculums. These methods range from using BIM in everything from architectural studio, sustainable design, and construction management to civil engineering (Önür, 2009; Sharag-Eldin and Nawari, 2010; Barison and Santos, 2010; Sacks and Barak, 2010; Wong et al., 2011). For instance, Önür (2009) and Sharag-Eldin and Nawari (2010) described how BIM is integrated into the architectural curriculum. Sacks and Barak (2010) introduced BIM as an integral part of freshman-year civil engineering education.

Several academic institutions have integrated BIM in their curricula using different approaches; however, there is no commonly agreed on methodology for teaching BIM in AEC programs (Barison and Santos, 2010). Most schools offer BIM in only one or two different courses. Many courses limit coverage to a short period (one to two weeks) (Becerik-Gerber et al., 2011). The BIM course is limited to a single discipline in 90% of the cases (Barison and Santos, 2010). The majority of schools introduce BIM on a basic level by teaching a specific software tool, limiting students' perspective on BIM to viewing it simply as another computer-aided design (CAD) productivity-enhancing tool for creating two-dimensional (2D) and three-dimensional (3D) drawings (Sacks and Pikas, 2013). However, BIM by nature goes far beyond digital drafting (Eastman et al. 2011). A comprehensive literature review on the subject can be found in the work of Barison and Santos (2010) and Sacks and Pikas (2013).

Because BIM is different from traditional CAD, it does require new ways of thinking and teaching. For instance, BIM facilitates across-discipline and interdisciplinary collaboration and teamwork that must be incorporated in teaching BIM courses. Furthermore, BIM provides rich visualization of building elements and parametric modeling of behavior, which can enhance students' learning experience and understanding of virtual construction and how building elements fit together just as they must on a physical site.

BIM FOR STRUCTURAL ENGINEERING AND ARCHITECTURE

Building structures are, and have always been, essential components of building design. This is attributed to the roles and meanings of safety, economy, and performance of buildings to the society at large. From early societies to the present, buildings have provided shelter, encouraged productivity, embodied cultural history, and definitely represented an important part of human civilization. In fact, the roles of structures are constantly changing in terms of shaping certain quantities of materials and making them support the architecture against gravity and other environmental forces (Addis, 2007). Also, from the earliest times a sense of beauty has been inherent in human nature; some buildings were conceived according to certain aesthetic views, which would often impose on structures far more stringent requirements than those of strength and performance. Thus, designing structures is becoming deceptively complex as buildings today are also life support systems; communication and data terminals; centers of education, justice, health, and community; and so much more. They are expensive to build and maintain and must constantly be adjusted to function effectively over their life cycle (Prowler, 2012). Hence, for many, the subject is frequently marked by complexity.

Structural analysis courses at the undergraduate level focus mostly on computation and understanding the principals of statics and strength of materials, without stressing the importance of understanding conceptual behaviors of structural systems and their aesthetic implications. Addis (1990) noted that at all times in architectural engineering history there have been some types of knowledge that have been relatively easy to store and to communicate to other people, for instance, by means of diagrams or models, quantitative rules, or a mathematical form. At the same time, there are also other types of knowledge that, even today, still appear to be difficult to condense and pass on to others; they have to be learned afresh by each young engineer or architect, such as a feeling for structural behavior and aesthetic functions, for instance. Currently, in the education of young structural engineers, educators have tended to concentrate particularly on knowledge that is easy to store and communicate. Unfortunately, other types of knowledge have come to receive rather less than their fair share of attention (Addis, 1990; Rafiq, 2010).

On the other hand, architectural students in the design studios are concerned primarily with artistic expressions and philosophical description, independent of the building as an organism and how it is constructed. Structure is not adequately discussed and presented in their work. They apparently are not motivated by the current way of conveying structural concepts and design processes (Schueller, 2007). The purely mathematical approach of the classical engineering schools is not effective in architectural and building construction colleges. Thus, students of these schools are driven to consider themselves as artists or contractors with less interest in scientific and engineering principles. However, all artists must acquire mastery of the technology of their chosen medium, particularly those who choose buildings as their means of expression.

The structure of a building is the framework that preserves its integrity in response to external and internal forces. It is a massive support system that must somehow be incorporated into the architectural program. It must therefore be given a form that is compatible with other aspects of the building. Many fundamental issues associated with the function and appearance of a building, including its overall form, the pattern of its fenestration, the general articulation of solid and void within it, and even, possibly, the range and combination of the textures of its visible skins, are affected by the nature of its structure. The structure also influences programmatic aspects of a building's design because of the ability of the structure to organize and determine the feasibility of pattern and shape of private and public spaces. Furthermore, structures can be defined to control the inflow of natural light or improve ventilation or many other functions that are needed by the architectural spaces.

The relationship between structure and architecture is therefore a fundamental aspect of the art of building. It sets up challenges between the technical, scientific, and artistic agendas that architects and engineers must resolve. The method in which the resolution is carried out is one of the most tested criteria of building design success. This issue has been recognized by many engineers and architects, such as Khan (2004), Addis (1990), Schueller (1995, 2007), Billington (2003), Schodek (2004), Sandaker (2008), and Nawari and Kuenstle (2011), among others.

With recent technological advancements, engineers and architects have smarter tools to create and analyze artistically efficient structural forms and demonstrate how load combinations affect the stability and behavior of a structure. Specifically, BIM has the potential to provide solutions to the issues related to the conceptual linking and integration between architectural and structural engineering principles and advance different types of structural knowledge-sharing objectives without compromising their distinct requirements. BIM is a process that fundamentally changes the role of computation in structural design by creating a database of the building objects to be used for all aspects of the structure, from design to construction, operation, and maintenance. Based on this collaborative environment, a new framework is proposed to advance structural design education. This framework is referred to as the SAS framework or, alternatively, as the "buildoid framework" (students' preferred name). The framework explores structural design as an art while emphasizing engineering principles; it thereby provides an enhanced understanding of the influence structure can play in creating form and defining spatial order and composition.

NEW FRAMEWORK

The history of architecture intermixes with the history of mathematics, philosophy, and engineering at various levels. Designers have adopted concepts and language from these disciplines to assist in their own discourses. The term *synergy* refers to the collaboration of multiple objects in a system to produce an effect different from or greater than the sum of their discrete effects. In the context of the proposed framework, it refers also to the essence or shape of an entity's complete form.

In psychology, the term *Gestalt* is used in a similar sense, referring to theories of visual perception that indicate the human eye sees objects in their entirety (unified whole) before perceiving their individual parts. The phrase "The whole is greater than the sum of its parts" is often used when referring to synergy or Gestalt theories. Similarly, the SAS framework provides a useful language for understanding the structure as a whole in connection to its close relationship with architecture.

The SAS framework focuses on the interplay between architecture and structures and emphasizes a learning process that is highly creative. In this framework, the form of the structure is constrained not only by its function, the site, and the designer's vision but also by how it works as a whole and by the need to provide a rational argument and calculations to justify expectations before the structure is built.

The proposed framework concept aims to advance other types of structural knowledge that center on how to engage the student's imagination and to use it no less creatively than a musician or artist producing ideas. On the one hand, structural correctness emphasizes the conceptual and quantitative engineering sciences of the structural design. The framework combines various threads of knowledge (see Figure 1.1), which may seem at first glance conflicting and incompatible. These threads arise from many origins—an understanding of space and human activities, scale, proportions, engineering sciences, knowledge of the behavior of actual materials, and the construction process.

In structural design, the essential skill lies in choosing structural forms and arrangement that manage to satisfy, to varying degrees, many often-incompatible constraints. As with a musician when composing music, this skill relies on a mixture of precedent, experience, and inspiration. For this purpose, the vocabulary and methodology are introduced using the concepts of "structural melody," "structural poetry," and finally "structural analysis." These are the main components of the proposed framework along with BIM as the framework enabler. Figure 1.1 depicts an overview of this framework. Without the traditional emphasis on first understanding

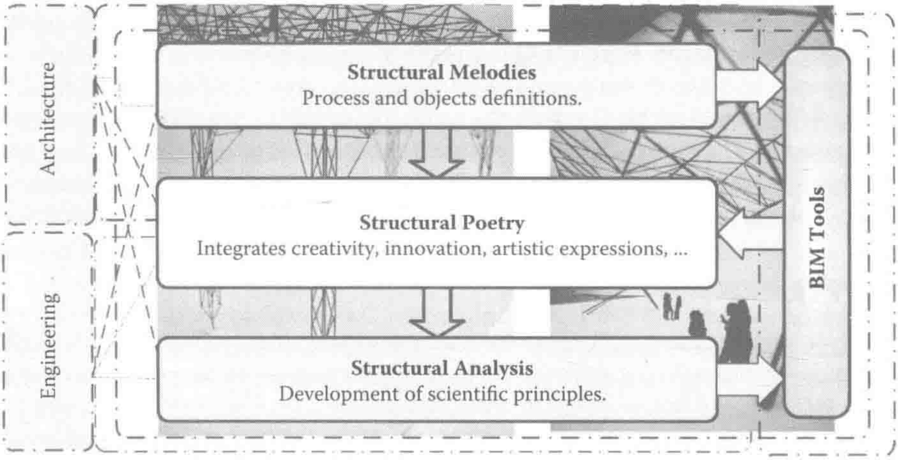

FIGURE 1.1 Structure and architecture synergy framework (SAS framework).

beams, columns, footings, bearing walls, and so on two dimensionally, using the laws of statics and strength of materials, the framework emphasizes the building as a whole and creates 3D structural systems using BIM tools and then develops them further into actual architectural solutions.

BIM CONCEPT

Structural design in education is standing on the brink of a new technology that will transform the way structures are designed and constructed. The change is more significant and more profound than the transition from hand computation and drafting to CAD.

Building information modeling is a process that fundamentally changes the role of computation in the AEC industry (Autodesk, 2013). It involves new concepts and practices that are so greatly improved by innovative information technologies and business structures that they will radically reduce the multiple forms of waste and inefficiency in the building industry (National Institute of Building Sciences, 2007). In this concept, rather than using a computer to assist producing a series of drawings that together describe a building, the computer is used to create a single, unified representation of the entire building so content comprehensive that it can generate all necessary construction documentations. The primitives from which the BIM software composes these models are not the same ones used in traditional CAD (points, lines, curves). Instead, the BIM application models with virtual building components that hold attributed information about actual elements and systems. Examples include trusses, columns, beams, walls, doors, windows, ceilings, and floors. The software platform that implements BIM recognizes the form and behavior of these objects, so it can ease much of the tedium of their coordination. Walls, for instance, join automatically, connecting structure layers to structure layers and finish layers to finish layers. Many of the benefits are obvious—for instance, changes made in one view propagate automatically to every other elevation, section, callout, and rendering of the project. Other advantages include the ability to use the same model to interact with other applications, such as structural and energy analysis software (Autodesk, 2013).

As a general concept modeling type, BIM deals with higher-level operations than traditional CAD does. It deals with placing and modifying entire objects rather than placing drawings and modifying sets of lines and points. At the same time, BIM platforms allow you to do some standard drafting if needed. Consequently, the geometry is generated from the model and is therefore not open to direct handling (Autodesk, 2013).

Another important concept is that a BIM model encodes more than form; it encodes high-level design intent. Within the model, walls and floors are modeled not as a series of 3D solids but as virtual walls and floors with material types and properties. That way, if a level changes height or walls change width, both of the objects automatically adjust to the new values. If the wall moves, any floor that has a relationship to that wall adjusts automatically.

Students must be introduced to these basics of BIM using one of the available BIM authoring tools. This introduction can take about twelve contact hours. The last phase of this introduction is an overview of the platform interface along with

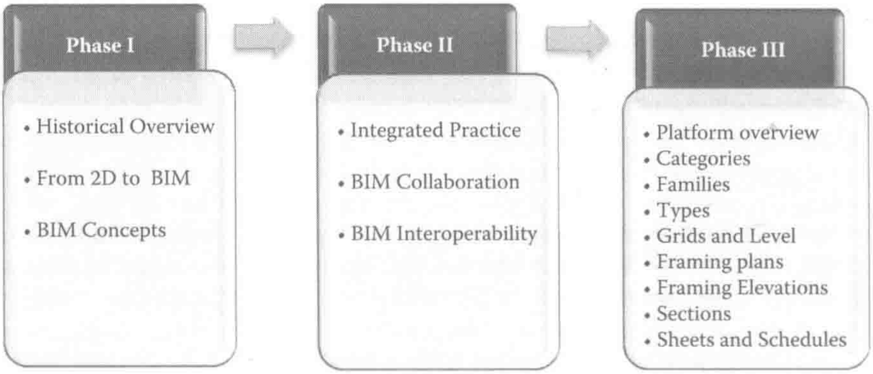

FIGURE 1.2 BIM introduction blocks. (From Sharag-Eldin and Nawari [2010]. BIM in AEC education. In *Joint Structures Congress with the North American Steel Construction Conference*.)

emphasizing the comprehension of new concepts, such as model element, categories, families, types, and instances (see Figure 1.2). Phases I and II in Figure 1.2 cover the introduction to basics of BIM. In phase III, a specific platform is chosen, and students learn more in depth about object-oriented modeling techniques. This last phase of instruction normally takes a full semester.

Following the introduction, students can be engaged in learning about the various analysis tools that integrate with BIM platforms. Some of these tools are available as extensions to the basic versions of the software.

STRUCTURAL DESIGN FUNDAMENTALS

COMMON ATTRIBUTES OF ARCHITECTURE

Throughout the United States, accredited schools of architecture and design are influencing and educating the future generation of architects, who may go on to create the next masterpiece. Their knowledge of many branches along with their judgment is the practice and theory of architecture (Waldrep, 2006). It is not this issue that is being called into question; rather, the question considers the current role of the architect.

To understand the role of architects, it is imperative to acknowledge their focal points in design. For example, Salingaros and Mehaffy (2006, p. 30) suggest that architects may consider "order on the smallest scale that is established by paired contrasting elements, existing in a balanced visual tension; large scale order occurs when every element relates to every other element at a distance in a way that reduces entropy; the small scale is connected to the large scale through a linked hierarchy of intermediate scales with various scaling ratios." One of the overall objectives is to give rise to different experiences that users of a building undergo. The practical functions, such as the entry and exit, and circulations are also influenced by the structural form and order.

The basic practices an architect of today would follow are appraisal, design brief, concept, and design development (Chappell and Willis, 2000). These actions