# Tensegrity cushions: formwork for cast-inplace concrete walls

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ABSTRACT: This article presents a tensile, fabric formwork for casting structural concrete walls that utilizes a tensegrity space-frame system. Based on analytical and scaled physical modeling, a series of full-scale proof-of-concept concrete casts demonstrate the methods, techniques, and sequence of construction along with the variation and tolerances achieved. Presented as an alternative to current cast-in-place concrete construction techniques, the tensegrity formwork provides a base logic for novel and emergent behavior in the final form while demanding comparably minimal material, equipment, and labor skill-sets. Empirical testing of the proof-of-concept casts document three points of control: the formwork system's ability to maintain industry standard coverage of structural steel; an acceptable tolerance on the location of structural connections; and, a reliable formula for estimating concrete volume. Further development of the assembly will include the testing of structural connections along with embedding programmatic and environmental design responses.

KEYWORDS: Concrete, Fabric Formwork, Tensegrity, Labor

#### INTRODUCTION

Steel has a tensile capacity of 60,000 pounds per square inch (psi), which is nearly double it's compressive yield of 36,000 psi<sup>i</sup>. These numbers are quite striking when measured against wood's 6k tension and 22k<sup>ii</sup> compression or concrete's meager 600psi in tension and 4k compressive strength<sup>iii</sup>. Buckminster Fuller exalted these tensile qualities in the structural concept of Tensegrity -- a coined phrase for tensional integrity. Tensegrity is a structural system that maximizes the resistance of forces through tension members and thus minimizing less efficient compressive members. Ideas of tensegrity are recognizable in many of the model explorations and built architectural work of Frei Otto. The breadth of Frei Otto's design research demonstrates the complex and diverse forms attainable through variations in tensegrity assemblies. Contributing to this area of research, a tensegrity system is adopted as an internal structure to a tensile, fabric formwork for cast-in-place concrete. This tensegrity system facilitates the construction of accurate and variable cast forms by comparably low-skilled labor, while minimizing the total material consumed by the formwork.

In this article, contemporary fabric formwork systems by Mark West are reviewed along with a survey of tensegrity systems by Frei Otto. Industry standards for structural concrete walls are assessed and selected along with techniques adopted from current fabric formwork research. A series of physical concept studies and small-scale structural models, problem solve design decisions for multiple full-scale proof-of-concepts concrete casts. Dissection of the full-scale cast structures documents the tolerances achieved and leads multiple iterations of testing through additional controlled casts. The research concludes with computational modeling that explores emergent behavior -- formal variations influenced by possible structural, programmatic, and environmental systems -- of the tensegrity formwork.

## 1.0 SURVEY OF CAST IN PLACE CONCRETE SYSTEMS

Concrete's stone-like beauty and potential for limitless form<sup>iv</sup> has driven the construction industry to challenge the methods with which we design, fabricate and deploy formwork. With each new advancement in formwork systems, concrete's weight of 150 lb/ft3 remains a dominant factor. Prior to curing, this static load of the concrete slurry is quite considerable --most notably the accumulated outward pressure at lower levels of wall formwork (150lb/lnft x

Ht wall). A survey of contemporary cast-in-place concrete wall formwork systems compares how this high, yet brief, strain of the concrete slurry is mitigated differently when set against various other considerations; The time and labor's skill required to deploy the formwork, the volume of materials consumed by the formwork, the sophistication of the equipment required, and ability to integrate building systems. To survey the impact that variation of the final form has on these factors, I have assembled the diagram below drawing from personal professional practice and construction experience with concrete, and through research on the topic.

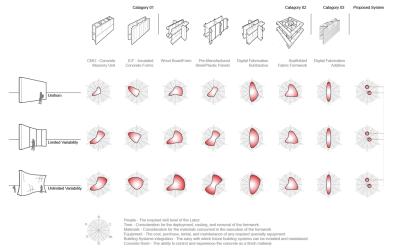


Figure 1: Diagram Cast-in-Place Concrete systems. (Author 2018)

Contemporary solutions to these constraints have developed formwork either integral or sacrificial to the final cast form. Ubiquitous in construction today, concrete masonry units (CMU) and insulated concrete forms (ICF) (Diagram: Category 01) are modular units that are not removed after the casting of the concrete and therefore remain part of the final form. Their modularity and sizing allow for relatively low-skilled labor when constructing a uniform wall. Although when confronted with constructing highly-variable forms, these systems are limited by the unit size or the time and the laborer's skill required to alter the individual units. It is important to note that the concrete finish of the CMU blocks is expressed in the final form. Whereas, the rigid insulation foam of the ICFs remain as the constructed wall's finish -- not concrete.

Sacrificial or removable formwork systems -- whether wood boards, plywood sheathing, metal or plastic panels -- require an independent structural support system (Diagram: Category 02). These support systems include the vertical studs bracing the panels, the horizontal wales that bind the studs, and buttressing behind the wales locating the system on site. Some efficiency can be found in the reusing of the panels and subsequent supporting when constructing uniform and low variability forms. Although, when considering high-variability forms, the novelty of each member becomes excessive in the consumption of time and materials. In the past decade, Subtractive Digital Fabrication's ability to manufacture high-variability with little to no excess time has opened the door to complex form-making and casting. Subtractive Digital Fabrication is burdened by requiring a very highly-skilled labor pool along with specialty equipment; such as, multi-axis computer numerically controlled (CNC) and plasma cutters. This equipment allows for off-site fabrication but adds additional expense to purchase and maintain.

More recently, Additive Digital Fabrication methods have moved the machine to the site and in-turn shed the necessity of formwork (Diagram: Category 03). With this nascent technology formwork is supplanted by either placing or dispensing the construction materials directly. Although full of potential, these methods have not produced the software or hardware to create

both the cementitious wall and structural reinforcement required within it<sup>v</sup>. Sophisticated equipment and highly skilled labor is mandatory.

For many of these reasons, Mark West pioneered contemporary investigations into fabric formwork as the founding director of the Center for Architectural Structures and Technology (C.A.S.T.) at the University of Manitoba. Although his work moved on to exploration into efficiencies in precast structural members, early work with columns and walls highlighted the benefits and struggles with intricate tensioning systems.

## 2.0 WEAVING A LOGIC OF ASSEMBLY

The American Construction Institute states a contractor is required to design, fabricate, and install the formwork vi. Through a comparison of Mark West's fabric-formed cast-in-place columns from the late 90's and his later experiments with precast thin shell vaults this paper will discuss the contribution that the design, fabrication, and installation of the formwork had on the cast work.

As the founding Director of the Centre for Architectural Structures and Technology (CAST) at the University of Manitoba, Mark West's research dominates today's discussion of tensile fabric-formed concrete. In his recently published The Fabric Formwork book, Mark West assembles two decades of concrete explorations. West's early success with site responsive cast-in-place concrete columns, highlight the speed and variability of tensile fabric formwork in comparison to contemporary systems that rely on steel, wood, or rigid foam paneling.

For discussion purposes, this paper identifies three key elements found in Mark West's formwork assemblies; the scaffolding, the rigging, and the fabric. The scaffolding is an initial structure that is temporarily erected to give support for the rigging. In turn, the rigging mediates the interstitial space between the scaffolding and the desired points of control of the fabric. The fabric, held by the rigging, is free to distend as the static load of the concrete slurry defines the surface and therefor volume for casting.

A comparison of Mark West's approach to scaffolding in his cast-in-place columns to his precast shell vaults, the early column's scaffolding demonstrated an ad-hoc nature in response to site. Constructed of wood and steel, the temporary scaffolding systems required extensive structural support as they were required to carry the load of the concrete slurry along with resisting bending due to the loading of the tensile rigging members. These constraints combined with site variability demanded on-site problem solving. As C.A.S.T.'s work moved off-site for the later precast structures, the scaffolding formwork was no longer needed to respond to the site constraints. This allowed for greater consistency of the cast form as the scaffolding became self-referential rigid frames.

Highlighted within the techniques utilized in the column work, Mark West's elaborate rigging vii systems telegraphed ornamental details into the cast products. These cast articulations develop a distinct design language unique to the fabric formwork system. In the later precast work, the fabric surface was defined by plywood structural spines as the rigging was minimized to merely adding tension in the fabric surface. Like the consistency of the scaffolding, variation in the final form was limited due to the reuse of the plywood spines as the fabrics form controlling elements.

Focusing on flat-sheet work -- fabric that does not require extensive sewing or cutting prior to installation -- the Festival Plaza sound-sculpture column, which he cast in 1995, demonstrated an articulate two-layer fabric system -- an inner stretch-knit liner wrapped by a laced unyielding corset. This approach to the assembly allows details of the assembly beyond the initial surface to be telegraphed through to the final form. In contrast, the taunt pre-tensioned fabric of the direct-cast thin shelled vaults actively mitigated the expression of any details. Additional construction of "feather-boards" wiii was undertaken at the moments of transition between the

tensile fabric and the plywood scaffolding to further minimize the articulation of the fabric formwork

Mark West mentions that he began his investigation by asking, "What actually needs to be controlled?" When considering the column examples, the concern for 'control' plays out in the methods of assembling the scaffolding, rigging, and fabric. The final cast of these columns demonstrates a unique balance of intended and found form. Whereas, in the later spanning assemblies, his concern for control has moved to the final product, specifically focusing on the structurally efficient use of the concrete.

By re-examining this question of control, Phase One of this research identifies industry standards for construction of a structural concrete wall. Revised annually, construction standards aim at maintaining the life, safety and welfare of the public through the establishment of minimum construction standards. Aware that the act of construction is not perfect, many of these standards define acceptable tolerances -- these are, "permitted variation in one part of construction or in one section of the specification must not be construed as permitting violation of the more stringent requirements for any other part of the construction." ACI 347 Formwork for Concrete.

## 2.1 Phase one: scaffolding

Phase One of this research continues Mark West's use of scaffolding as a means to resist the tensile forces of the rigging and fabric formwork. The goal of this phase is to develop a logic of assembly for the rigging that allows for formal variation while maintaining accepted standards of construction. To this end, four key industry standards for above ground cast-inplace structural wall have been selected for assessment. Three of which address structural concerns; the minimum coverage for Steel Reinforcement (rebar), the allowable tolerance of Structural connectors (anchor-bolts), and the allowable variation in Structural form (plumb), whereas, the fourth identifies acceptable Surface Variation. Regarding the structural concerns, a minimum thickness of concrete must be maintained for sufficient transfer of forces between the concrete and rebar. An industry standard of 1-1/2" of concrete coverage is adopted for this research<sup>x</sup>. When addressing the location of anchor bolts, ACI established a tolerance with which the construction must be executed. A dimension of +- ½" is seen as conservative in the industry and is set as the target for this research. The assessment of a structures Plumbness requires both a small-scale control -- no more than 1/2" variation over 10' -- and a more comprehensive view stating a maximum 1" variation for the entire height.

Phase One of this research adopts the three structurally relevant industry standards but challenges the idea of allowable variation in the finish surface xi. When the concrete is understood to be rough or hidden from view -- Classified as B, C, and D surfaces -- a relatively high 1/4" to 1" tolerance is acceptable for abrupt or gradual inconsistencies. In comparison, locations that are expected to in the public view, Class A surfaces, demand a minimal variation of 1/4". These categorizations suggest that only near-perfect surfaces are acceptable for public viewing; yet, we have seen with Mark West's concrete columns that when fabric formwork is employed, the surface can take on highly variable and unique design vocabulary.

The logic of assembly for the Rigging is investigated through physical modeling. The diagram below notates the design research through initial Conceptual Models, followed by Scaled-Assembly test, and finishing with a full-scale Proof-of-Concept cast. Phase One concludes with an assessment of the methods, techniques, and sequences success.

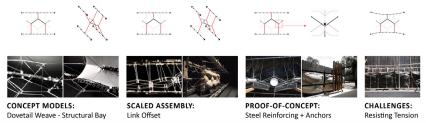


Figure 2: Diagrams and Photos of Scaffolding Design Process. (Author 2018)

#### 2.2 Lab notes-

Initial Concept Models (See diagram: 01 Concept Models) explored various weaving systems to establish a systematic method of installation while allowing variation in the pattern. As diagrammed in plan and axon, when a Dovetail weave pattern is mirrored a complex spatial volume is defined. This technique began with a series of steel cables running the centerline of the proposed cast. Initially left loose, these centerlines 'dovetail' between vertical rigging triangulated in the scaffolding. This dovetail weaving between alternating sides, is mirrored with each vertical strata of centerlines. These opposing dovetail weaves establish structural bays within the future cavity of the cast.

In later Scaled-Assembly Tests, the location of the fabric in relation to the weave was refined through the installation of Offset Links at each of the centerlines' dovetail connections (See diagram: 02 Scaled-Assembly Test). These Offset Links create a network of control point a defined distance from the internal tensioned structure. These points allow the fabric surface to be held by a secondary weave beyond the internal tensioned centerlines. The length of the offset allows for a direct control of the minimum coverage of concrete at each connection point.

In a full-scale Proof-of-Concept cast, 4000-lb of concrete was formed in four contiguous structural bays. The dovetail weave established nodes for the placement of #5 rebar vertically at a maximum of 24" on center. In addition, the Dovetail weave allowed for the placement of a 4" diameter void centered in each bay (See diagram: 03 Proof of Concept). At full scale, Mark West's experimentation with surface materials inspired the selection of a woven PE geotextile for the fabric. This fabric telegraphs a consistent hatch pattern across the bulging surfaces. The perceived quality of the surface brings into question the skill of the labor typically required to construct a finished surface (class A). The use of a weave system decreased the requirements of on-site problem solving that were noted by Mark West regarding his early concrete columns<sup>xii</sup>.

Although the tensile formwork system did not fail, the strain is evident in the deflection of the scaffoldings structural members (See diagram: 04 Challenges). With over an inch of deflection in the upper crossing members, the reliance on bending to resist the tensile forces of the rigging in the Scaffolding-Based tensile formwork system does not optimize the structural efficiency of the formwork assembly and demonstrates an unacceptable lack of control of the anchor locations.

Phase One of this research did find success with a logic of assembly that paired a dovetail weaving pattern with a link offset. The Dovetail weave for the Rigging balanced a 3D spatial control of connections points using a set of communicable parametric relationships that are capable of variation. The Link Offsets established secondary external connections points that facilitates a controlled structural coverage of concrete for internal steel reinforcement.

Phase two of this research looks to Frei Otto's explorations in Tensegrity to challenge the efficiency of a Scaffolding-base fabric formwork system.

# 2.3 Specifically high-low cable-net cushions

Graduating from the Technische Universitat in Charlosttenburg in 1952, Frei Otto's thesis and subsequent professional design work investigated maximizing the use of tension -- steel cables -- as the predominant structural members. This idea was in high contrasts to ubiquitous structural systems that rely on compression (a column supporting a roof) or bending (a beam spanning between supports). Frei Otto's work, specifically the Olympic Stadium in Munich (constructed 1967), demonstrated to the world that the volume of material required to construct a building can be greatly reduced with the increase of tension systems within the design. Frei Otto did not stumble upon these ideas.

Frei Otto's design process tackled exploration, refinement, and testing through physically constructed models. Each model growing more complex and integrative of the materials and systems required. History loves to make note of the soap bubble models, as they represent the conceptual idea of structural forms, but it is the larger scale models, like that of the west grandstand roof of the Olympic stadium where measurements were taken, and the details matured. This method of investigation demonstrated the benefit of the architects understanding and critique of construction -- although scaled down -- as a critical design tool.

Frei Otto models, regardless of scale, demanded the actual methods of construction as a means for insight into onsite problems. (Roland 1970)

Frei Otto's investigation into Tension Structures can be classified into three areas, 1D Linear structures, 2D Surface Structures, or 3D Space Structures<sup>xiii</sup>. Linear structures represent a direct tension between two points acting within a single plane. Surface Structures are the manipulation of a single surface stressed in one or more directions. Space Structure have internal members, arranged in three axis that define a volume within their assembly.

Linear structures easily identified as rope swings, a chandelier chain, or as complex as a suspension bridge. Surface structure take on forms such as domes, convex and concaves. These synclastic forms are created when a surface is arced in multiple axis towards the same direction. Anticlastic, or saddle-like, forms are created if those arcs are set in opposing orientations. As with many of Frei Otto's bubble experiments, these Surface Structures represent the most efficient use of material to structural define a skin<sup>xiv</sup>. When anticlastic surfaces are constructed with a high degree of pre-tensioning, the structural efficiency of the form paired with a lightweight material allow for complete freedom in their orientation in space<sup>xv</sup>. Unlike Surface structures that require anchoring or resistance from external sources, the third type, Space Structures, are closed structural systems. When the multi-axis members of a Space Structure are ridged, we call the system a space-frame, when tension cables are the dominant elements, they are called Tensegrity systems.

Labeled Cushions, Frei Otto investigated a series of Space Structure installations where he encapsulated a cavity by facing two Surface Structures opposite of each other. The Mushrooms (constructed: 1959) relied on a compression ring to resist the internal tensile forces of two opposing conical surface structures. Advancing to more complex saddle-like surfaces, Frei Otto drew from his past success with what he defined 'high-low' surface like that at Cologne (1956). When these 'high-low' surfaces are mirrored to capture a volume, rather than a tent pole to resist the tension forces, a grid of compressive struts where incorporated. A Space Structure comprised of two opposing surface structures, the Congress Hall in Chicago (Yale University, Bogner and Moore, 1960) represented a physical manifestation of Frei Otto's definition of Tensegrity, "Islands of compression, floating in a sea of tension".

# 3.0 PHASE TWO: TENSEGRITY CUSHIONS

Acknowledged as the pure blasphemy when set against Frei Otto's goal of lightweight construction, Phase Two of this research explores the logic of assembly Frei Otto's high-low cable-net cushion tensegrity systems as an internal structure for cast-in-place concrete construction. Phase two builds on the use of Link Offsets as a means of controlling concrete coverage, while turning the dovetail weave inside-out through the use of the tensegrity system's minimal floating compression members. The goal of this assembly systems is to

eliminate the requirements of the structurally inefficient scaffolding while establishing an easily communicable system that allows for a high degree of variability.

#### 3.1 Lab notes-

A series of concept models explored the structural principles behind Frei Otto's High-Low cable net cushions. These scaled models identified a sequence of construction and opportunities for site designed variation. Temporary cables suspend a compression member in space allowing for the adjusting of individual cushion's alignment. This 'tuning' of each structural bay allows for on-site engagement of the construction process as these nodes will become future locations for structural, programmatic, or environmental connections.

A full-scale proof-of-concept tested the ability of a series of Tensegrity Cushions to stack vertically between #5 rebar set at 16" on center. Plumb was maintained as the #5 rebar are held in place much like the center pole of a circus tent, equal ties in equal yet opposite directions. Once tuned, industry standard tie wire replaced the temporary cables rigidly locating each floating compression member. Between the Plumbness and the integrity of the individual tensegrity bays, no scaffolding was required. Similar to Phase One's Link offset, concrete coverage is maintained by extending the floating compression member beyond the internal tensegrity frame. A woven PE-geotextile is held in place as a secondary weave of steel tie-wire connects the cushion nodes.

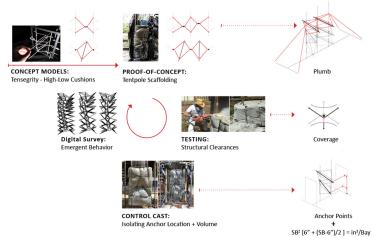


Figure 3: Diagrams and Photos of Tensegrity Cushions Design Process. (Author 2018)

Once cast, the proof-of-concept was documented and dissected. Through various cross-sectional cuts an empirical assessment demonstrated the minimum rebar coverage was maintained.

After establishing the Tensegrity system would maintain plumb during the structurally intense casting process and that minimal structural clearances could be maintained, A series of Control Casts isolated the outer weave's impact on concrete volume and the tolerances achievable with structural anchoring systems. An equation based on the structural bay width estimate an appropriate volume of concrete mix. This equation proved accurate at estimating volume of 10" structural bays in early material studies and with 12", 16" and 24" structural bays in full scale proof-of-concept casts.

These Control Casts allowed for measurements pre and post casting of the anchoring systems. In multiple cast a total of 16 anchor location were document achieving a tolerance of +- 1/8", well within the acceptable range.

Through the Control Casts, the increased static pressure of the concrete slurry at the lowest bays dictated the secondary-weave pattern's reinforcement of the PE-geotextile fabric.

Investigation into emergent behavior of these tensegrity cushions through computational modeling allows for speculative studies of the systems response to site, programmatic, and environmental demands while maintaining the established sequence of construction and maintaining of the defined industry standards.

By defining internal relationships of the tensegrity system, a parametric logic is established that allows the individual bay to respond to internal neighboring bays and external site, programmatic, and environmental demands. Like other complex systems, clearly established relationships in the base unit have the potential to develop unique emergent behavior in their responses.

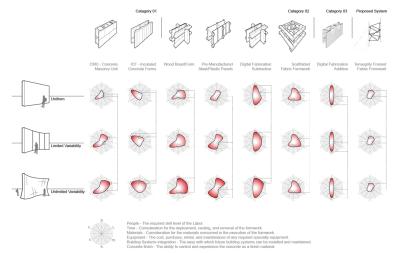


Figure 4: Diagram comparing current and proposed cast-in-place concrete systems. (Author 2018)

## CONCLUSION

Eugene Viollet-le-Duc's dissection of why Greek artisans did not use arches notes the desire by the elite to maintain a caste system. Held by the sculptor, the art and knowledge of construction was removed from the subjugated, on-site labor. The removal of craftsmanship from the labor class dehumanized their work, in turn, removing their opportunity for pride and status<sup>xvi</sup>. A century later, Eladio Dieste's paramount work in brick structural form, idealizes the enriching possibilities of knowledge springing for the ground-up. Eladio notes the satisfaction his workers and the community take in the richness of the work executed<sup>xvii</sup>. Between these examples we witness how the dominant method of construction employed in a region can regulate the dissemination of intellectual and economic prosperity, along with exerting direct impact on individual self-worth within a society. In today's fervor for computational design and digital fabrication, it is easy to see Dieste's concerns regarding the "tyranny of the drawing board" translate into "tyranny of the abyss of model space" as the act of construction has decreasing less influence in design. How do we utilize the tools at our fingertips, while not removing the knowledge and pride of the act of construction? The research presented cycles between the investigation of low-tech construction assemblies and computational testing of variations with the intent of establishing a logic of construction assessable to low-skilled labor while facilitating complex variability.

This research proposes a tensile, fabric formwork for casting structural concrete walls that utilizes a tensegrity space-frame system as an alternative to contemporary cast-in-place construction systems. An initial survey of cast-in-place concrete construction systems -- comparing the time and labor's skill required to deploy the formwork, the volume of materials consumed by the formwork, the sophistication of the equipment required, and ability to integrate building systems -- established baselines for assessment. This survey was paired with research on Mark West's fabric formwork to identify the role of scaffolding, rigging, and

fabric in the cast form. Furthering Mark West's scaffolding-based systems, through scaled assembly and full-scale proof-of-concept casts, Phase One developed a unique approach to tensile assembly by incorporating a Dovetail Weave technique and controlled Link Offsets. Phase two of this research, began with a study of Frei Otto's variations of tensegrity systems, where the logic of his High-Low Cable-net Cushions was adopted to challenge the structural inefficiency of bending in Phase one's scaffolding. Again, through scaled assembly models, the methods, techniques, and sequences were explored, revised and executed in full-scale proof-of-concept concrete casts. These cast were assessed for their ability to maintain: industry standard coverage of structural steel; an acceptable tolerance on the location of structural connections; and, a reliable formula for estimating concrete volume. Through computational modeling, the logic of the assembly system explored additional formal variations. The success of the proof-of-concept casts demonstrate an opportunity for further research this complex systems design response to greater structural, programmatic, and environmental systems. With these industry standards met, although the Tensile Cushion units required a layered sequence of construction, once understood, relatively low-skilled labor has to potential to investigate and execute complex variations. In the vein of Eladio Dieste's elevation of an assessible assembly, the proposed construction system has the potential to place design research into the hands of the working labor.

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## **ENDNOTES**

i (ASTM, 2018, Grade 60, Mild/Low Carbon Steel)

<sup>(</sup>Forest Products Laboratory, 1999, Coastal Douglas Fir)

iii National Ready Mix Concrete Association, 2018)

iv (Matter in the Floating World, 2011, 112) Ando, "...the potential for stone-like beauty without the geometrical limitation of stone itself."

<sup>&</sup>lt;sup>v</sup> (3D Printing and Buildings: A Technology Review and Future Outlook TAD, 2018)

vi (ACI 347-14. Formwork 26.11.1.1)

vii (West, 2016, 153)

viii (West, 2016, 248)

ix (West, 2016, 7)

<sup>&</sup>lt;sup>x</sup> (ACI 347-14. Formwork 26.11.1.1, Design Information) 2" coverage is required if the rebar is #5 or larger. 3" is required if the concrete is exposed to earth.

xi (ACI 347-14. Formwork 26.11.1.1, Design Information. ACI Class A, B, C, and D)

xii (West, 2016)

xiii (Drew, 1976)

xiv (Roland, 1970)

xv (Roland, 1970)

xvi (Viollet-le-Duc, 1990)

xvii (Dieste, 1987)