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BIM FOR TEMPORARY STRUCTURES: DEVELOPMENT OF A REVIT API PLUG-IN FOR CONCRETE FORMWORK

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Abstract: As one of the most promising developments, Building Information Modeling (BIM) enables the possibility of automating the design process. Prior research efforts have largely focused on permanent design components with minimal attention given to temporary structures, such as concrete formwork and scaffolding. Nevertheless, the design processes for temporary structures are repetitive and often tedious, which require consideration of multiple parameters of individual permanent components, the latest design standards, design methods, procedures, and available materials. This paper proposes a BIM-based tool to help with planning and designing concrete formwork. The tool integrates the information associated with individual elements in BIM models with design processes recommended by the American Concrete Institute (ACI) through an Application Programming Interface (API) in Revit. Using the tool, planners will be able to decide the most applicable formwork design based on the design of the permanent facility along with the availability of construction materials, site conditions, and safety considerations. The research also provides a new tool for contractors when planning concrete operations and extends the BIM design scope.

1 INTRODUCTION

Formwork is primarily used for concrete construction to support permanent concrete forming and curing until the structure gains sufficient strength to support itself, as well as to support construction live load. Proper designing, planning, placing and removing formwork is crucial to ensure the success of concrete projects. However, the safety record of concrete construction is relatively poor; about a quarter of all construction failures involve concrete construction (Lew, 1976). In addition, inadequate consideration has been given to temporary works in the industry (Gilbertson et al., 2011). Studies have shown that if designers devote sufficient effort to the design of formwork or other temporary structures, worksite safety could be improved. For example, a study performed by the Health and Safety Executive in the UK (Bennett, 2004) showed that among all the investigated cases related to temporary structures, about one-sixth of the accidents could have been prevented from occurring if designers took enough action in the original design to prompt safety. Similarly, researchers from California State University-Long Beach, after analyzing 435 accident case reports from the federal Occupational Safety and Health Administration (OSHA), concluded that insufficient design is one of the statistically significant causes of injuries (Haduong et al., 2018). Other major factors that contribute to formwork failures include lack of monitoring during formwork erection and communication confusion among stakeholders (Hadipriono and Wang, 1986). Additionally, as suggested by Sheehan and Corley (2013), improved communication and organization of project documents among stakeholders could have helped to prevent an incident through the investigation of the formwork collapse when building a multi-story parking garage. It is apparent that approaches to improve the design quality of formwork and to facilitate communications and collaborations are essential to ensure site safety.

In recent years, BIM has been widely adopted by designers and contractors during the early stages of construction projects since BIM creates a collaborative environment and enables seamless information exchange among various stakeholders (Singh et al., 2011). BIM has changed the way buildings are designed, constructed, and operated, and has changed the traditional workflows and project delivery processes (Hardin and McCool, 2015). However, temporary structures are commonly not clearly delineated and planned in the building drawings or BIM models (Kim and Ahn, 2011) and the majority of past research efforts have put an emphasis on permanent structures. Only limited research has given attention to temporary structures, such as safety railings for fall protection (Zhang et al., 2015), temporary stair towers for roof construction activities (Kim and Cho, 2015), and scaffolding plans (Kim et al., 2018). More importantly, only a small portion of research studies have targeted concrete formwork (Meadati et al., 2011; Chi et al., 2012; Kannan and Santhi, 2013; Singh et al., 2017) and a limited number have proposed conceptual models for formwork planning (Chi et al., 2012; Singh et al., 2017).

In addition, it has been shown that safety guidelines, standards, and best practices related to formwork designs can be successfully incorporated with the existing multi-dimensional models in BIM (Zhang et al., 2011; 2015). Given the importance of concrete formwork in the industry and the fact that designing and planning temporary structures requires excessive manual effort, the development of a BIM-based tool to help designers automate the design process with safety rules, which also benefits planners and other stakeholders, is in high demand.

2 BACKGROUND ON FORMWORK DESIGN AND BIM-API APPLICATIONS

Concrete forming practices may differ from one country to another and even from one region to another in the same country due to predominant local material use, material availability from suppliers/manufacturers, and contractor preference (ACI, 2014a). Except for unusual or complex structures, in general, the contractor is responsible for planning and designing the formwork. The detailed work may involve multiple parties including formwork engineers, form manufacturers, form suppliers, and formwork specialty subcontractors. As for complex structures, the engineer/architect who designed the concrete structure and specifications may also get involved and be partly responsible for formwork design and planning.

Guides, standards, and specifications on formwork design and planning have been published by different professional associations. In 2015, the American Society of Civil Engineers (ASCE) published “Design Loads on Structures during Construction” to provide designers and constructors guidance on the minimum design load requirements that need to be considered during construction of buildings and other structures. This reference manual describes the minimum loading and pressures for which the formwork shall be designed. In addition, with respect to concrete, concrete formwork, and shoring, OSHA provides requirements in Subpart Q (concrete and masonry construction) (OSHA 29 CFR 1926). Targeting concrete formwork systems, Chapter 6 in the book “Building Code Requirements for Structural Concrete (ACI 318-11)” (ACI, 2011) covers general guidance of designing formwork, the book “Guide to Formwork for Concrete (ACI 347R-14)” (American Concrete Institute (ACI), 2014b) provides detailed guidance for formwork design and construction, and another book published by ACI (2014a) provides detailed step-by-step procedures to design different components of formwork systems.

Apparently, the formwork design process requires tedious effort (Singh et al., 2017), which consists of rigorous structural analysis. In addition, to facilitate the design process and ease a form designer’s work, several books provide design tables which indicate calculated safe spans for typical formwork designs. Even though design tables are easy to use, the formwork designs obtained may not be suitable for all site conditions. With respect to formwork plans, because there is no standard and formal practice to generate temporary structure plans in the industry, the planning process is often performed manually and based on the planner’s own experience, which is commonly subjective, time-consuming, and error-prone (Kim and Fischer, 2007; Zhang et al., 2011).

With the development of construction innovations, a number of researchers have explored ways to facilitate the formwork design and planning process. To name a few, Meadati et al. (2011) proposed a concrete formwork repository which consists of various functions, such as design visualization, quantity takeoff, alternative design and constructability analysis, and shop drawing generation. Chi et al. (2012) proposed to develop formwork BIM objects with safety considerations. In addition, Kannan and Santhi (2013) conducted constructability assessments of climbing formwork systems in BIM. However, only a few studies have seriously considered incorporating standard design procedures into the design process. Studies performed by Singh et al. (2016; 2017) proposed frameworks to link formwork calculation tools with BIM models to automate formwork design processes. However, their studies were only in a conceptual phase and the researchers did not take constructability and safety issues into consideration.

Furthermore, a number of researchers have utilized the benefits of parametric modeling offered by BIM and have successfully incorporated additional functions in the design and planning phases through BIM extensions using API implementations. For example, for sustainability considerations, Bank et al. (2010) proposed to integrate a BIM model with sustainability indicators in a system dynamics decision-making tool for alternative evaluation and optimization. Additionally, as mentioned by Wu and Issa (2012), the LEED Automation program initiated by the U.S. Green Building Council (USGBC), provided opportunities to streamline cloud-BIM engagements with the LEED certification process. In 2016, Oti et al. developed a BIM extension that enables sustainability appraisal for structural design options. Additionally, there are other developed BIM extensions which also show promising results in expanding the BIM design capabilities and enabling nD building performance measures, such as facility management / asset management (Lin et al., 2014; Farghaly et al., 2018), supply chain management (Irizarry et al., 2013), architectural visualization (Du et al., 2018), and so on. Therefore, integrating formwork design procedures and safety rules with BIM models is promising.

3 RESEARCH OBJECTIVES

Taking advantage of API capabilities, this study attempts to make a direct link between AutoDesk Revit, a BIM modeling software, and formwork design and planning through the development of a Revit API. To limit the scope of the present Revit-API development, the study focused on timber formwork systems for concrete floor slabs. Timber concrete formwork systems are extensively used in the industry as they are easy to erect in the required size and shape, easy to handle and dismantle, and relatively inexpensive compared to steel and alumni. The objectives of the present study describe herein are to:

1) Develop a framework that integrates formwork design procedures and safety rules with BIM models, and
2) Develop a Revit-API to assist with formwork designs and implement the API on a selected case study.

4 CONCEPTUAL FORMWORK DESIGN AND PLANNING FRAMEWORK

The proposed BIM-based formwork design system is depicted in Figure 1. The first step is to retrieve the required parametric design information from the existing 3D BIM model for formwork design. The second step involves using the extracted data from the first step to perform the formwork design which follows the design procedures recommended by ACI ((American Concrete Institute (ACI), 2014a; American Concrete Institute (ACI), 2014b). During the design process, safety recommendations are provided to designers when selecting appropriate formwork components that enable safer design and planning. The safety recommendations are extracted from the formwork design standards contained within the OSHA standards and other industrial formwork safety best practices. After the design is complete, the proposed formwork design can be modeled with the existing 3D model. Furthermore, work breakdown structure and schedule information is incorporated with the updated BIM model, as well as the safe planning rules to prompt formwork planning safety during formwork installation, shoring, reshoring, and removal phases. This paper places an emphasis on developing a formwork design BIM-extension for the design phase. The work of using the developed extension to facilitate the planning process will be discussed in a subsequent paper.

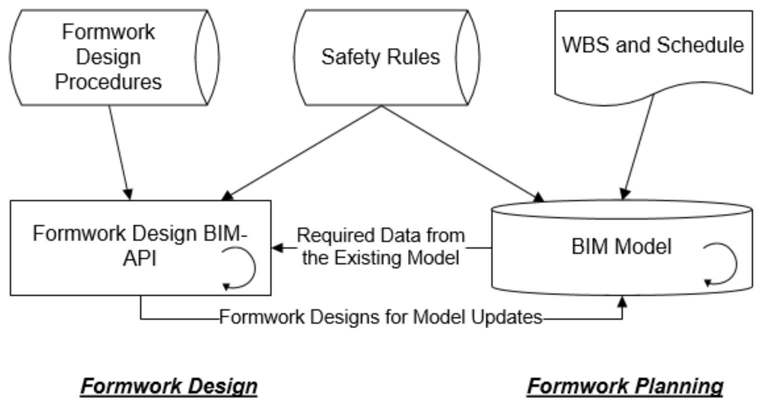

Figure 1. Proposed BIM-based Formwork Design and Planning Framework

5 FORMWORK DESIGN REVIT-API DEVELOPMENT

5.1 Slab Formwork Design Procedures

Design of timber formwork for slabs consists of a systematic structural analysis of sheathing, which is used to retain the concrete, and members to support the sheathing firmly in place during concrete pouring and curing. As suggested by ACI (2014a), the basic steps of slab formwork design include the determination of design load, sheathing thickness and spacing of its supports (joist spacing), joist size and spacing of supports (stringer spacing), stringer size and span length (shore spacing), shore spacing and size, bearing stresses checks, and lateral bracing design. The detailed process and data flow can be found in Figure 2. It is worth mentioning that sheathing or lumber adjustment factors and safety factors are applied when designing timber formwork to ensure that the formwork is strong enough to carry out the design load and lateral pressure generated by freshly placed concrete, construction live loads, and environmental loads.

5.2 Formwork Design Safety Rules

Regarding safety considerations applied to formwork designs, the researchers carefully searched the OSHA regulations and other safety guidelines. The search results revealed three categories of safety requirements related to formwork: design requirements for cast-in-place concrete, standards related to fall protection, and guidance about material handling. The details about the safety rules incorporated in the proposed Revit-API are listed in Table 1.

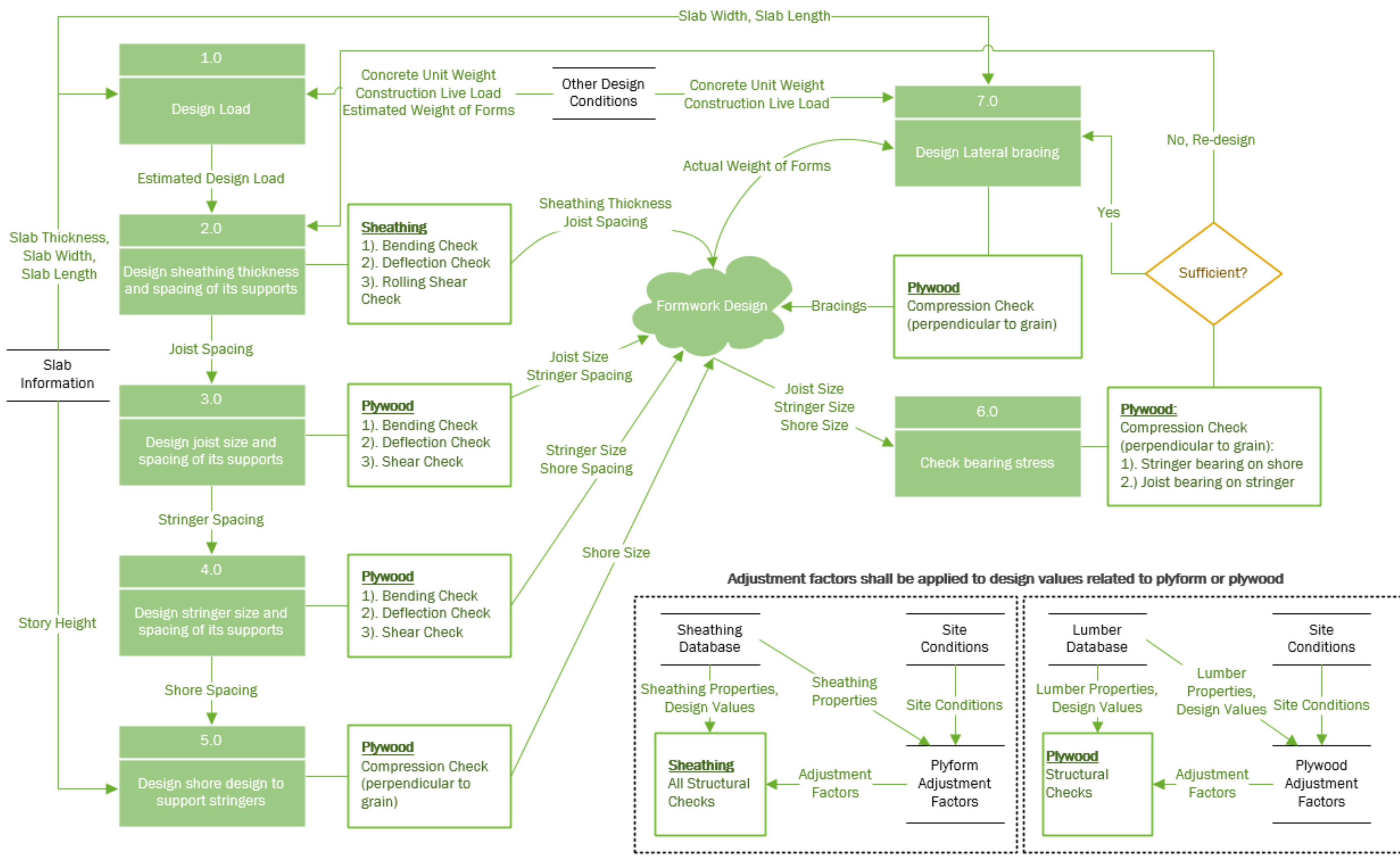

Figure 2. Slab Formwork Design Procedures

Table 1: Safety Rules Used in the Proposed Revit-API

Category	Standards/Guidance Details	Measures Taken in the Proposed Revit-API
Requirements for cast-in-place concrete (OSHA, 1996)	1926.703(a)(1) – “Formwork shall be designed, fabricated, erected, supported, braced and maintained so that it will be capable of supporting without failure all vertical and lateral loads that may reasonably be anticipated to be applied to the formwork”.	The API is designed to follow the design procedures recommended by ACI
Fall protection (OSHA, 2004)	1926.501(b)(1),1926.501(b)(2), 1926.501(b)(5),1926.451(g) – “Each employee on a walking/working surface (horizontal and vertical surface) with an unprotected side or edge which is 6 feet (1.8 m) or more above a lower level shall be protected from falling by the use of guardrail systems, safety net systems, or personal fall arrest systems.”	If formwork is designed to be elevated 6 feet or more above the lower level, remind designers to plan for fall protection systems
Material handling (OSHA, n.d.)	Based on the lifting equation from the National Institute for Occupational Safety and Health (NIOSH), the recommended maximum load for manual lifting is 51 pounds.	If the selected formwork components exceed 51 pounds, recommend designers to use lightweight components or remind designers to use two or more people to lift the load when planning for manual lifting

5.3 Revit-API Development

The researchers selected AutoDesk Revit to serve as the development platform for the proposed plug-in. The Revit plug-in for designing formwork systems was programmed using C# language in the .NET Framework (version 4.5.2). Two Revit API references, which are required to ensure the interaction between the external application and the Revit environment, are loaded in the API: RevitAPI.dll and RevitAPIUI.dll. In addition, a plug-in manifest was written and added to the system so that Revit can read the plug-in at startup. Figure 3 shows the flowchart of the proposed Revit-API and the timber formwork system designed by the proposed application is based on allowable stress design (ASD) methods with adjusted design values. The proposed plug-in is still under development at this stage, which possesses a few limitations.

After opening the plug-in in Revit, the user makes a selection from the existing 3D model. If the selection is not an elevated slab, the user has to make another selection; otherwise, the application automatically extracts the parameters of the selected component. The built-in parameters retrieved include slab thickness, slab area, slab perimeter, and slab height (elevation from the bottom of the slab to the top of the lower level). Through the computation of the retrieved parameters, the slab width and length can be determined (currently, the extension is only applicable for rectangular shaped concrete slabs). Once the user confirms the slab data are correct, or manually enters the correct data, the user is guided through the systematic formwork design procedures (as shown in Figure 2) to determine the appropriate size and spacing of form components. During the process, minor inputs from the user are required. For example, when designing the joists, the user has to: 1) pre-determine which condition is known, joist size or spacing of support, 2) select lumber grade and species, and 3) consider other site or loading conditions associated with adjustment factors that are applied to the tabulated design values. In addition, safety checks are performed to confirm whether the initial design complies with the safety rules (Table 1) and whether additional safety considerations should be included in the planning phase.

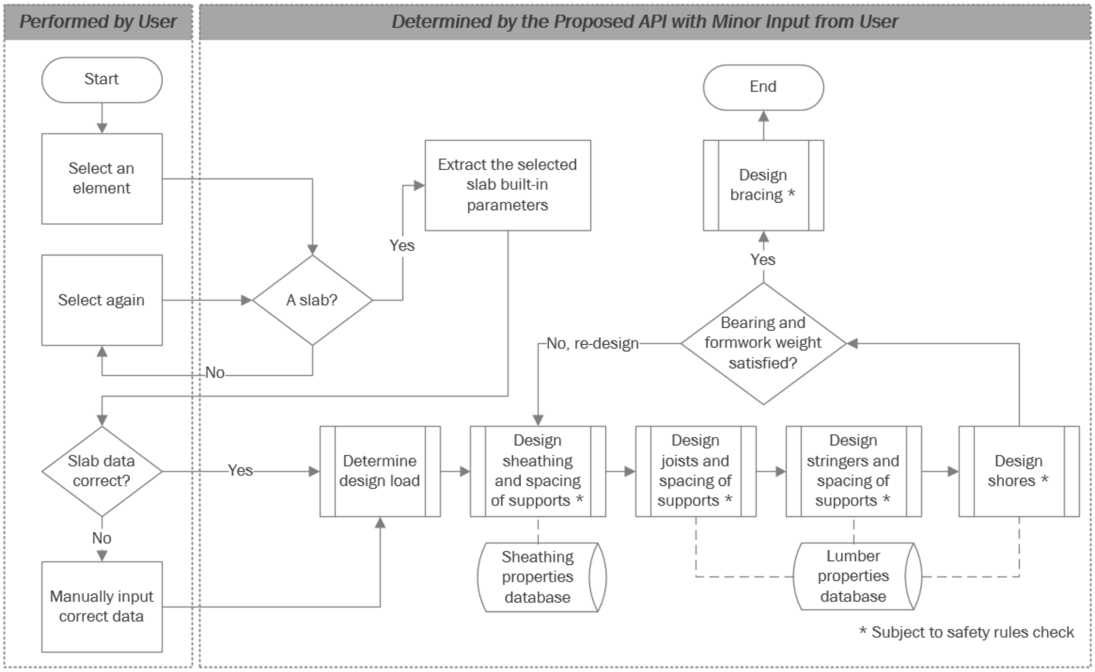

Figure 3. Flowchart of the Proposed Revit-API

6 CASE STUDY

A 3D model of a simple two-story building was created in Revit. The proposed Revit-API was tested on an elevated, flat rectangular-shaped, normal weight concrete slab (8" thick) from the model to demonstrate the design process and verify its applicability. Moreover, in order to confirm the correctness of the proposed Revit-API, a formwork design example (Example 7.4 in ACI *Formwork for Concrete* (ACI 2014a)) served as the ground truth. The same design assumptions are used in the case study, including: 1) Construction grade, Douglas Fir-Larch, S4S framing members; 2) forms will be reused (no adjustment needed for short-term load); 3) ¾" Structural I, B-B Plyform sheathing (4' x 8' panels); 4) job site conditions are normal (no adjustment needed for wet service); 5) stringer and shoring spacing will be 5 ft.; and 6) deflections are limited to 1/360 times the span length.

As shown in Figure 4, after initiating the developed plug-in in Revit and clicking on a slab in the existing model, a windows form is displayed for the user to confirm their desires to design slab formwork and the correctness of the slab information. If the retrieved information is incorrect, the user has the choice to input the identified data manually. Once the slab information is verified and/or input, in the next step, another form with control tabs (Figure 5) is shown to direct the user to go through the step-by-step design procedures.

In the current version, the design procedure form has a total of nine tabs, including tabs for the: 1) design load, 2) sheathing, 3) joists, 4) stringers, 5) shores, 6) bearing checks, 7) formwork preview, 8) bracing, and 9) planning suggestions. A typical design interface, consisting of the determination of sheathing size/joist spacing, is shown in Figure 5. Users select applicable conditions from the drop-down lists or manually enter the required information for the plug-in to run in the data input section. As a result, the recommended design value generated by the system through a set of computations will show in the computation result section for users to consider. Once users confirm the design decisions based on material availability and design preferences, the design decisions will be shown on the right side of the interface (see Figure 5). In the process, for safety purposes, the system will pop up message boxes to inform the user of: 1) the requirements for lateral support to permit using the beam stability factor (C_L) equal to 1, when the ratio of depth to thickness of the selected lumber component is more than 2 to 1; and 2) the weight of the designed component, when it exceeds the recommended maximum load for manual lifting (51 pounds). With such information, the user may consider selecting a safer design option.

After the initial design of the basic slab formwork components is decided, bearing checks, i.e., whether allowable bearing stresses exceed the actual bearing stresses between the joists and stringers and between the stringers and shores, and a formwork weight check, i.e., whether the estimated formwork weight is larger than the actual formwork weight, can be performed in Tab 6. Then, the user can preview the design components in Tab 7, and continue the design for bracing in Tab 8. In the current version, the bracing design only supports determining the design load for slab formwork bracing. In Tab 9 (planning suggestions), the interface lists all of the safety suggestions and the estimated quantity take-off for planners to use during the planning phase.

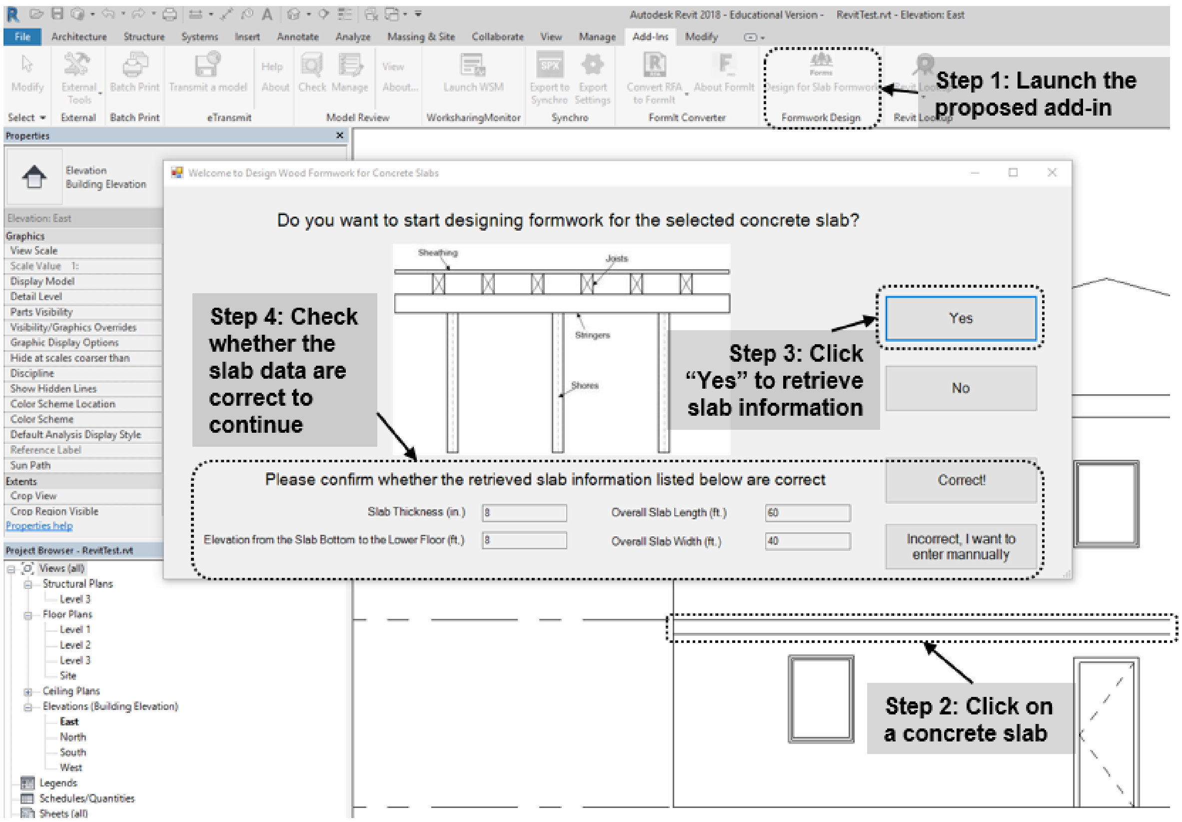

Figure 4. User Interface of the Proposed Revit-API (Retrieving Slab Information)

Based on its application on the case study project, it was found that throughout the design procedures guided by the proposed Revit-API, using the design assumptions mentioned earlier, the plug-in delivers a desirable formwork design result. The design is consistent with that in the example provided by ACI (2014a). It is worth mentioning that the design values generated in the process might be slightly different from what is shown in the example. Because, to be conservative, the proposed API considers construction live load when computing vertical deflection, which is different from the design process contained in the ACI book (ACI, 2004a).

7 CONCLUSIONS AND FUTURE WORK

The present study proposes a framework to incorporate the concrete formwork design process and safety rules with BIM authoring tools for designers when designing and planning temporary structures. A Revit plug-in aimed at utilizing the existing data from BIM models to design timber slab formwork systems was developed. Applying the proposed plug-in on a case study with a 3D BIM model of a two-story concrete-framed building demonstrates the interfaces and workability of the tool. It is anticipated that the proposed tool will allow both designers and contractors to select appropriate formwork members and assess the design in an efficient manner without tedious structural analysis efforts.

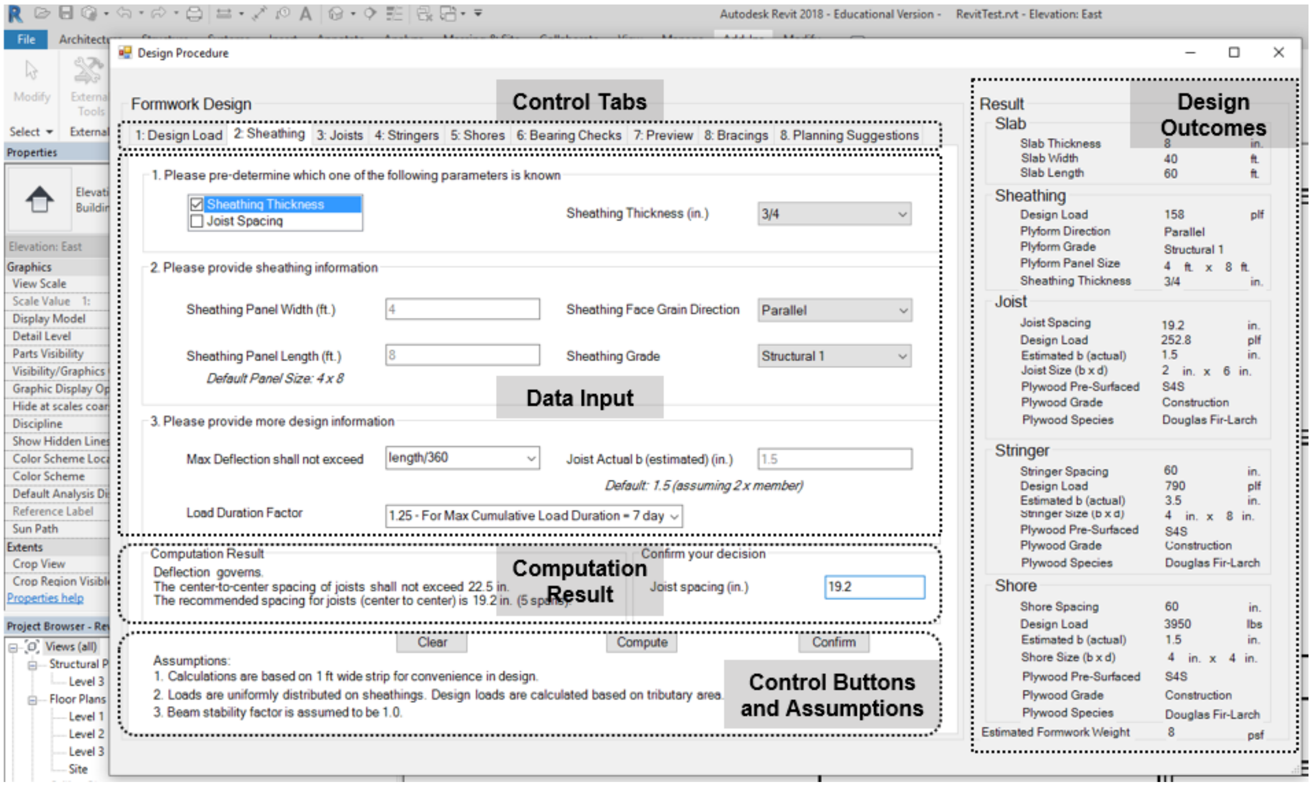

Figure 5. User Interface of the Proposed Revit-API (Process for Formwork Design)

Nevertheless, there are some limitations associated with the current study and future research will be conducted to address the limitations. As for the developed Revit Plug-in, the current version only supports a single rectangular-shaped concrete slab with limited lumber options to select. Future work will be conducted to include irregular-shaped slabs with more design options. Moreover, it is expected that more design and safety features can be incorporated in the design tool, such as diagonal bracing and formwork accessories including form ties, anchors, and hangers. Also, more design plug-ins can be developed for vertical formwork designs such as walls, so that the developed tools can be used to support designs for all concrete elements where formwork systems are needed.

Meanwhile, for the proposed BIM-based formwork design and planning framework, the present work is only focused on the formwork design phase. Future work can be conducted that is built upon the proposed tool to facilitate the planning process as mentioned previously. Tasks may include modeling the designed formwork components in the existing 3D BIM models, and incorporating formwork designs with WBS and schedules for site planning including planning for form reuse, performing shoring analysis, detailed quantity take-offs, and cost estimates. With the development of such plug-ins, the visual presentations and simulations of formwork designs and planning will also ensure effective communication and collaboration among stakeholders. Furthermore, opinions from formwork designers and contractors will be solicited to examine the effectiveness of the proposed formwork design and planning plug-ins.

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