BIM-based Decision Support System for Concrete Formwork Design

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Abstract –

The type and quantities of formwork system are necessary information for construction process of a concrete-framed building and the solution to this problem usually lays on the shoulders of specialized consulting firms or contractor's engineering department. These calculations are generally performed using available procedures and guidelines. The conventional formwork design process is manual and time-consuming, which requires considerable experience and attention to details. The emergence of building information modeling (BIM) in the AEC industry has allowed automation of many time-consuming tasks through application of object-oriented 3D modeling. In this project, a system was developed to automate formwork design process for the concrete-framed buildings. This method first extracts required data for the formwork design from the building information model of the project, which includes concrete elements' dimensions, quantities, and spatial information. It then applies formwork design rules and a database of modular formworks to determine dimensions and type of the formwork for each element. This system demonstrated promising performance in automation of formwork design in two test models.

Keywords –

Formwork design; Construction; Automation; Building Information Modelling; Reinforced Concrete

1 Introduction

Formworks are auxiliary structure made of wood, metal or composite materials; which serve to temporarily maintain shape, geometric dimensions, position in space, surface texture, and solidity of the structures that are made of shapeless or bulk materials, namely fresh concrete [1]. Formwork (also called shuttering) systems typically consist of forming elements, supporting structures, and fasteners [2]. After hardening of the concrete, formwork elements are usually removed (called detachable formwork), but there are also permanent formwork systems which are not removed and become a part of the main structure [3]. Both of these systems are widely used in modern concrete construction [1], but the removable formworks are more common and are classified based on their function, design, and material. Formwork systems for various structural members are slightly different from each other. For example, column formworks include struts whereas props are used for beams and slabs construction [1].

Traditional timber formwork systems are known for ease of fabrication and installation, and economical benefits in small construction. Aluminum and steel formworks usually cost more than wooden systems and are used in large-scale and high-precision construction. Moreover, these formworks can be used multiple times and they are more efficient for fast installation and removal of formwork, which in turn reduce the cost of form working after each use [3].

Conventional formwork design is a time-consuming and heuristic process, and is often based on the skill and experience of the engineers [4], and strength and the quantity are the main parameters in the design of a formwork system [2, 3]. A well-designed formwork system contributes to the quality, and timely and cost-effective construction of a reinforced-framed concrete building [1, 3]. Designing of a concrete structure and its formwork system are usually carried out separately, where the structural engineers design the concrete structure, and then the contractor designs a formwork for each element based on the dimensions and geometry of that component [5]. Therefore, development of automated formwork design tools would assist site engineers with the process of determining a suitable formwork system.

Earlier research efforts summarized best practices for design of a formwork system and proposed step-by-step guides and specific tables to speed up the process of formwork design [6]. Later, a Fuzzy logic-based model was proposed to assist site engineers in selection of a suitable vertical formwork system [7]. In addition, a mathematical formwork design method integrated with formwork operation layout planning demonstrated promising performance in high-rise building construction [8].

The multifaceted capabilities of the BIM have encouraged the use of this platform in the design and planning of on-site construction processes. The abilities of BIM to generate, store, share, and reuse information of building components are useful for repetitive tasks such as document generation, visualization, and quantification [9]. Application of BIM for different analysis, such as construction energy analysis [16], planning of construction processes [17, 18], and cost estimation [19], could reduce human errors of manual processes. Therefore, later efforts employed building information modelling to improve formwork design and planning processes. For example, a rule-based model was developed to assess the constructability of the horizontal formworks [10]. A cascade method was proposed which extracts required data (such as quantity take-off and construction phases) from the BIM model and uses them to design a formwork system for the project [5]. Industry Foundation Classes (IFC) schema was employed to optimize formwork design of concrete walls in building construction [11]. Later, a method was proposed to increase the proportion of the modular forms to increase formwork efficiency [12].

In addition to the formwork design, BIM-based data could be used to estimate labor productivity in formwork operations [13], and to determine required consumption of formwork systems [20]. These research efforts, however, did not present customizable approaches. In particular, most of these systems used a certain type of modular formwork system and did not search among various modular alternatives, and also did not investigate traditional timber formwork systems.

This paper presents a customizable system which was developed using a visual programming environment to extract data of cast-in-place concrete elements form BIM model and then designs a formwork system using a database of modular formworks from different suppliers. Upon the user request, this system is able to design traditional timber formwork for the concrete elements.

2 Methods

The workflow of this method is presented in Figure 1. It extracts certain attributes of the cast-in-place concrete elements, which are identified based on the corresponding codes, such as type and reference level. Then the system calculates pressure of the concrete based on the dimensions of each element. Afterwards, the system selects formwork elements based on the preference of the user between modular and wooden formwork systems. It should be noted that the system is only able to process prismatic elements rectangular cross-sections. Following subsections discuss the modules of this system.

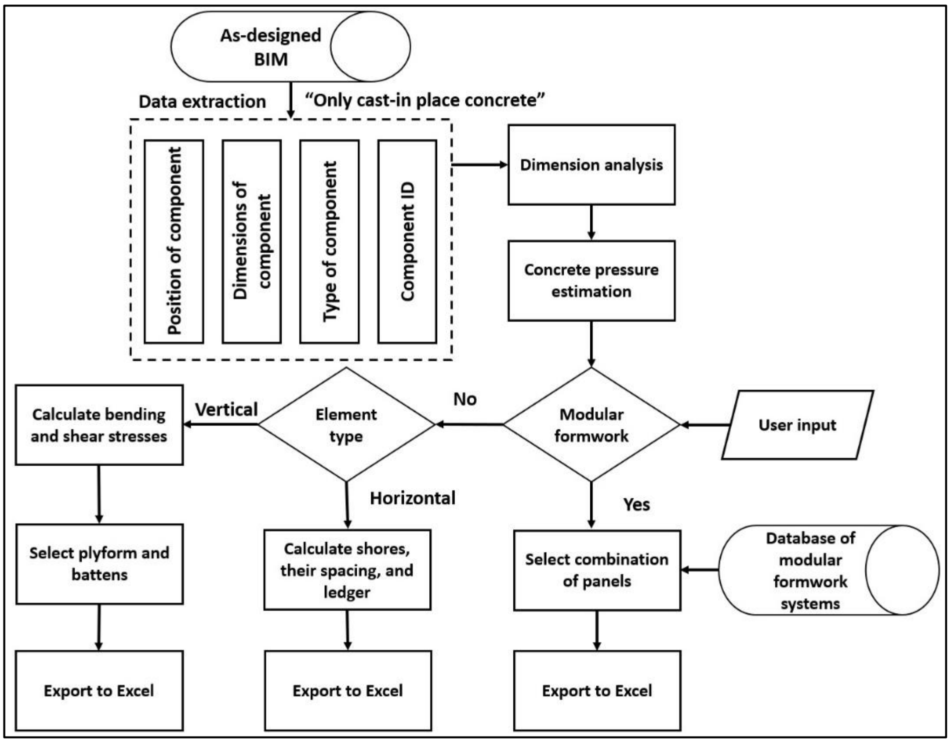

Figure 1. Workflow of the proposed system

2.1 Data Extraction

Dynamo environment [14] was used to automate the data extraction process. Dynamo is a visual programming and open-source platform for automated interaction with BIM models, which has the ability to extract various attributes of building elements.

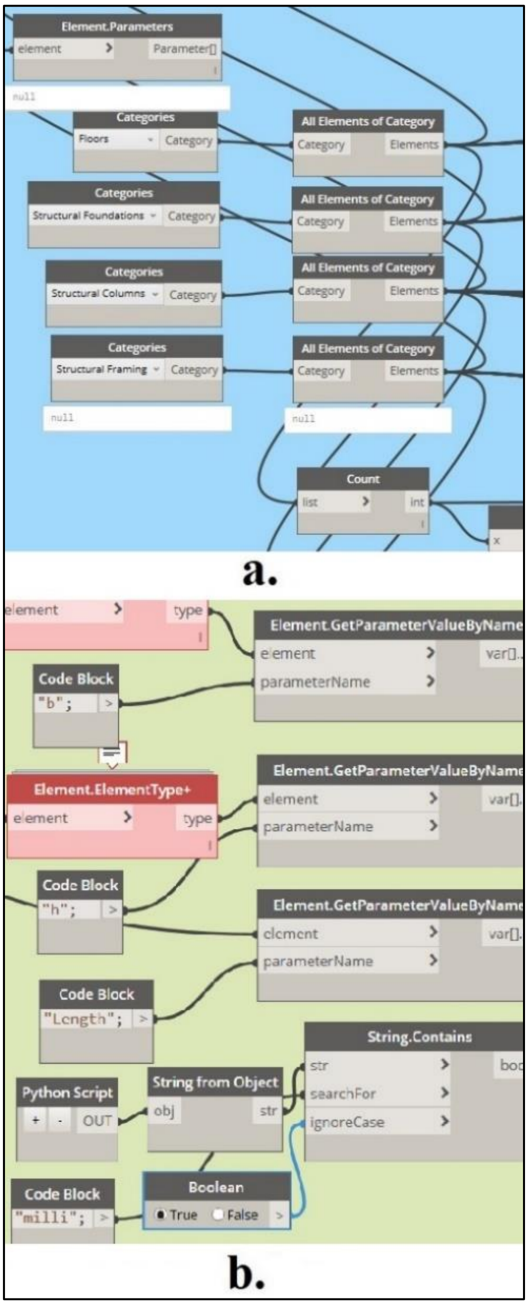

Figure 2. Data extraction using Dynamo functions: a) selection of elements of interest; b) selection of the target attributes

This module extracts the following data for each concrete element: dimensions (width, depth, height), ID (e.g. gridlines), type (e.g. column, beam, slab, foundation), and its level. Figure 2.a depicts a small part of this script which uses “Categories” and “All Elements of Category” to select all elements in the target categories, and then “Code Block” and “Element.GetParameterByValueName” are employed to extract the attributes of interest. For example, Figure 2.b shows a part of the script used the extract dimension of the columns.

2.2 Concrete Pressure Estimation

2.2.1 Vertical Load Estimation

There are two main types of vertical loads: 1) Dead loads include weight of fresh concrete, rebars, and the formwork; 2) Live loads consist of the weight of equipment, workers, and other related items. Based on the guidelines in ACI 347R-14 [15], the live load should not be less than 2.4 kPa (assuming no motorized cart is used) and the unfactored combined load (dead + live) should be more than 4.8 kPa (6.0 kPa in case of using motorized carts).

2.2.2 Lateral Pressure Estimation

Lateral concrete pressure depends on the dimension of concrete elements. The lateral pressure exerted on the formwork walls (see Figure 3), which was estimated based on the guidelines provided in ACI 347R-14 [15]. The lateral pressure of the fresh concrete depends on a few main factors, namely slump and temperature of the concrete and rate of concrete pouring. Two conditions were implemented in this system which should be selected by the user based on the properties of the concrete and pouring conditions. Equation 1 should be used for high slump concretes (greater than 17.8 cm) and concretes with deep vibration (greater than 122 cm), which simply calculates the equivalent hydrostatic pressure of the concrete. The lateral pressure for other cases is calculated using Equation 2. These equations were implemented in the Dynamo environment using “Python Script” node, which enables development of customized functions within the Dynamo platform.

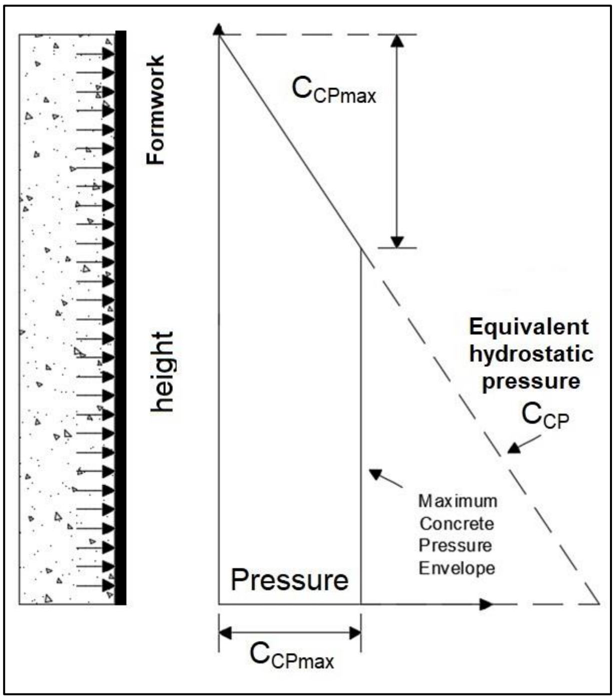

Figure 3. Schematic view of the lateral concrete pressure [15]

$$C_{CP} = \text{wh} = \rho\text{gh} \quad (1)$$

$$C_{CPmax} = C_c C_w [150 + \frac{900R}{T}] \quad (2)$$

Where C_{CP} is the equivalent hydrostatic pressure, w is unit weight of fresh concrete, h is the height of the element, C_{CPmax} is the maximum concrete pressure, C_c is chemistry coefficient, C_w is unit weight coefficient, R is the rate of placement ft/h (m/h), and T is the temperature of fresh concrete °F (°C).

2.3 Modular Formwork Design

Lists of modular formwork systems from four manufacturers were created. These lists include name of the manufacturer, admissible load (Kg/sq.m), width, and length of the available panels by each manufacturer (see Figure 4). Selection of formwork panels for concrete elements is carried out by a special "Python Script" node, which requires a number of inputs, including the name of the manufacturer, admissible load of the formwork panels in kg/sq.m, list of available panel dimensions for that formwork system, and the dimensions of concrete element.

When the system analyzes a vertical element (e.g. columns), the length corresponds with the vertical axis, and 0 to +0.30 m tolerance is accepted for this dimension. The same tolerance is applied for the side formworks of horizontal elements, namely beams. If there are more than one manufacturer for an element, then the program will eventually select the type that has appeared the most in all of the solutions. It is also possible to include unit cost of each type; thus, the system determines the lowest cost option.

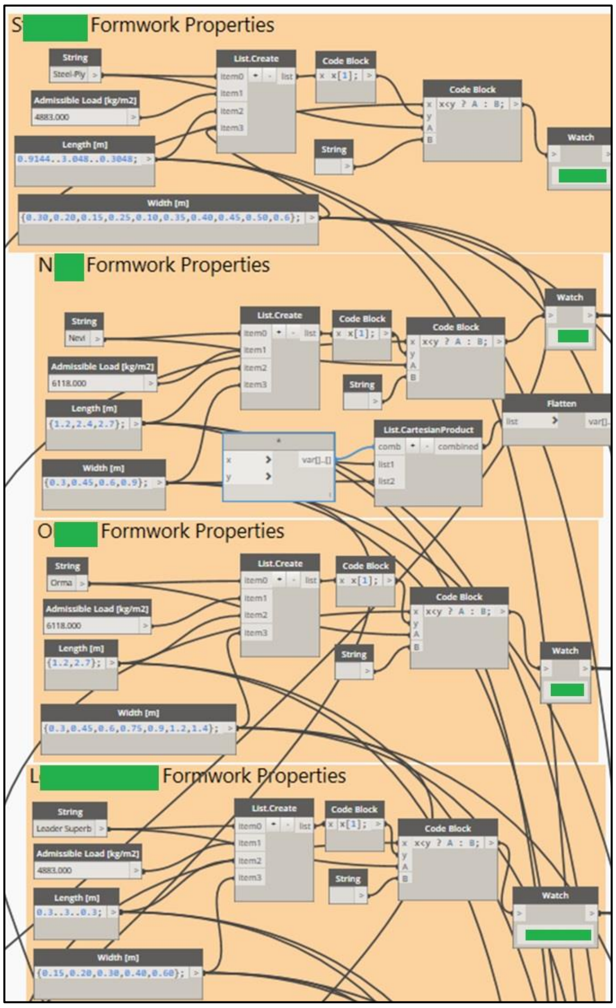

Figure 4. Lists of formwork systems from four manufacturers (names are covered)

The system identifies width (w in Figure 5) and length (l in Figure 5) as the smaller and larger dimensions of each formwork surface, respectively. The panel selection process iterates over the list of available dimensions from the manufacturers lists (using for loops) to find combinations that completely cover each formwork surface. It should be mentioned that this algorithm only uses panels from a same manufacturer to create a combination. This process is illustrated in Figure 5.

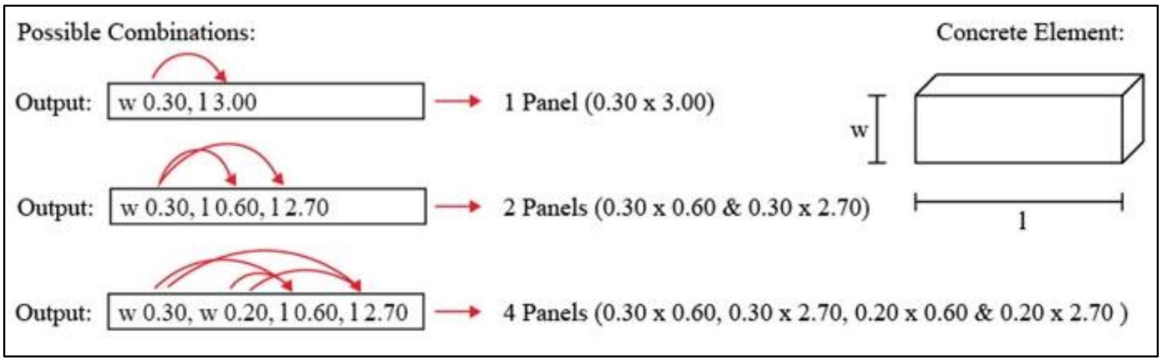

Figure 5. A sample workflow for selection of a panel combination

2.4 Conventional Timber Formwork Design

If the user chooses timber formwork option, the system calculates formwork elements based on whether they are vertical or horizontal.

2.4.1 Vertical Elements

The lateral concrete pressure acts against the plyform, which is supported with vertical wood battens laid flat. The plyform panels must transfer lateral pressure to the adjacent vertical wood battens. There are different types of wooden formwork products with different mechanical and physical (e.g. moisture content) properties, and dimensions, but a small number of options was used in this prototype. The plyform must have adequate strength to transfer the pressure with supports spacing up to 18 cm. The main criteria for selection of the plyform and battens is to pass the allowable bending and shear stresses. The calculations were implemented according to the design procedures available in [3].

In this approach, the system starts with a plyform with the smallest thickness, and if it fails, then it tries the next thickness until it reaches the allowable stresses. The same approach is used for the battens.

2.4.2 Horizontal Elements

This part of the system calculates three main items: shore spacing for the bottom part, ledger spacing, and shore design. These calculations were implemented according to the procedures provided in [1].

The shore spacing is calculated based on the bending due to the vertical loads and the bending capacity of the bottom surfaced two sides (S2S) lumber. The ledger spacing is also calculated based on allowable stress of the selected (surfaced on 4 sides) S4S ledgers and the stresses due to concrete load. Then based on the spacing of the shores, the applied load on each shore is calculated and compared against the allowable load of the unbraced shores.

2.5 Exporting Results

At the end, generated results are organized and exported to MS Excel for presentation. This process is implemented using a series of nodes, namely "Excel.WriteToFile" function. This way, the system arranges formwork information in a tabular format with all the necessary parameters such as element ID, level, family type, dimensions, and the proposed panel combinations and manufacturer.

3 Case Study

A five-story and four-story reinforced concrete-framed buildings were modelled in the Autodesk Revit environment. Isolated footings were used for foundation and beams and slabs were used for the flooring systems. Figure 6 depicts a 3D view of the five-story building model.

Figure 6. A 3D view of the test model

Figure 7 presents a sample of the results generated for modular formwork in the Excel environment. All the mentioned properties are organized and presented for the user.

Column ID	Column Base Level	Family Name	Column Width [m]	Column Depth [m]	Column Height [m]	Concrete Volume [m3]	Formwork System: Le
T-1	Base Level : Ground	300 x 300mm	0.3	0.3	3.000103381	0.270009304	w 0.30, l 0.60, l 2.70
U(-648)-1	Base Level : Ground	300 x 300mm	0.3	0.3	3.000103381	0.270009304	w 0.30, l 0.60, l 2.70
U(-648)-3	Base Level : Ground	300 x 300mm	0.3	0.3	3.000103381	0.270009304	w 0.30, l 0.60, l 2.70
U-6	Base Level : Ground	300 x 300mm	0.3	0.3	3.000103381	0.270009304	w 0.30, l 0.60, l 2.70
U-9	Base Level : Ground	300 x 300mm	0.3	0.3	3.000103381	0.270009304	w 0.30, l 0.60, l 2.70
U(-648)-11	Base Level : Ground	300 x 300mm	0.3	0.3	3.000103381	0.270009304	w 0.30, l 0.60, l 2.70
U(-648)-12	Base Level : Ground	300 x 300mm	0.3	0.3	3.000103381	0.270009304	w 0.30, l 0.60, l 2.70
T-12	Base Level : Ground	300 x 300mm	0.3	0.3	3.000103381	0.270009304	w 0.30, l 0.60, l 2.70
S-12	Base Level : Ground	300 x 300mm	0.3	0.3	3.000103381	0.270009304	w 0.30, l 0.60, l 2.70
R-12	Base Level : Ground	300 x 300mm	0.3	0.3	3.000103381	0.270009304	w 0.30, l 0.60, l 2.70
Q-12	Base Level : Ground	300 x 300mm	0.3	0.3	3.000103381	0.270009304	w 0.30, l 0.60, l 2.70

a.

Beam Reference Level	Family Name	Beam Width [m	Beam Height [m	Beam Length [m	Concrete Volume [m3]	Bottom L	Sides L
Reference Level : Level 1	400x500mm (reg)	0.4	0.5	4.5	0.9	w 0.40, l 1.50, l 3.00	w 0.40, w 0.40, l 1.50, l 3.00
Reference Level : Level 1	400x500mm (reg)	0.4	0.5	3.6	0.72	w 0.40, l 0.60, l 3.00	w 0.40, w 0.40, l 0.60, l 3.00
Reference Level : Level 1	400x500mm (reg)	0.4	0.5	2.031474108	0.406294822	w 0.40, l 1.80, l 0.30	w 0.40, w 0.40, l 1.80, l 0.30
Reference Level : Level 1	400x500mm (reg)	0.4	0.5	2.031474108	0.406294822	w 0.40, l 1.80, l 0.30	w 0.40, w 0.40, l 1.80, l 0.30
Reference Level : Level 1	400x500mm (reg)	0.4	0.5	6.0	1.2	w 0.40, l 3.00, l 3.00	w 0.40, w 0.40, l 3.00, l 3.00
Reference Level : Level 1	400x500mm (reg)	0.4	0.5	8.129	1.6258	w 0.40, l 3.00, l 3.00, l 2.1	w 0.40, w 0.40, l 3.00, l 3.00, l 2.10

b.

Figure 7. Sample tabular output: a) sample columns; b) sample beams

In addition, these formwork data can be imported in the Revit environment and saved as a parameter for the corresponding case-in-place concrete objects, and then be visualized for each element. Figure 8 displays a sample of a formwork combination added to the BIM model in Revit environment.

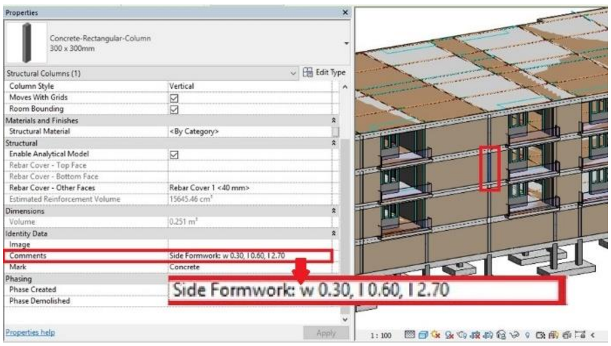

Figure 8. Sample of a formwork combination added to the BIM model

The system was also tested in designing of a conventional timber formwork. For this purpose, a simple BIM model, containing four columns and four beams, was used. Figure 9 shows the result for one of the column formwork designs (the results are drawn manually).

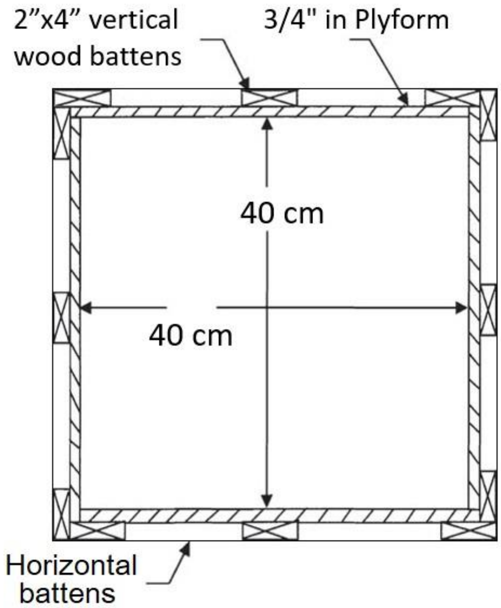

Figure 9. Cross-section of the wooden formwork for a 40x40 cm column

The results of this method and its modules was assessed to validate its performance. First, the outputs of the data extraction part were compared against the BIM models, where no difference was found. Second, the concrete pressure estimation correctly estimated vertical and lateral pressures. Next, selected panel combinations were validated, in which the system was able to provide a sufficient combination for each element; however, the results do not necessarily represent an optimized combination. Because this system does not consider form working state of other concrete elements and the availability of formworks. Moreover, performance of this system is limited to prismatic elements with rectangular cross-sections and further expansion is needed to analyze curved elements and the concrete components with irregular shapes and openings.

4 Conclusion

Formwork systems are essential part of cast-in-place concrete construction and automated design of formwork systems could improve this design process by saving time, and enhanced visualization and documentation. This research paper proposed a BIM-based decision support system to design modular and conventional wooden formwork systems for concrete-framed buildings. This system was implemented in the Dynamo platform, which extracts required data of cast-in-place concrete elements, and then calculates concrete pressure on the formwork surfaces. It finally tries different panel combinations to obtain a sufficient combination for each concrete element. This system demonstrated promising performance to facilitate formwork design processes in concrete construction, and the same data extraction and analysis could be used to develop automated tools for similar problems. The future research will focus on the analysis of irregular shapes, and also will investigates optimization of the formwork systems by considering overlapping and succeeding formwork activities.

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