Mapped Workflow for Safety and Reliability Assessments of Use and Re-use of Formwork

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ABSTRACT

Concrete formwork is a common type of temporary structure used on construction projects. Due to difficulties in considering actual construction site implications during formwork design, assessments of formwork integrity are often made in the field by site personnel based on subjective visual inspection. Furthermore, the construction and placement of concrete formwork continues to be a high risk activity, especially in regard to fall injuries and fatalities. This paper presents a research study in which work and material flow for the typical formwork construction process are mapped and the risks associated with each stage of the process are characterized in order to investigate the impacts of construction site conditions and operations on concrete formwork. Development of the process and identification of the risks were based on interviews of construction site personnel involved in formwork construction and on jobsite observations of formwork construction activities. Throughout its life-cycle, formwork is exposed to repeated loadings from concrete pressure, worker activities, and environmental conditions. The mapped work flow provides new information that can be used for the design and construction of formwork to: (1) improve construction worker safety and production, and (2) study the reliability of formwork with respect to repeated operational and environmental loading.

INTRODUCTION

Construction projects utilize temporary structures for many different activities. Formwork, scaffolding, sheet piling, and shoring systems are examples of temporary structures commonly used on projects. As the construction work progresses the temporary structures may be used multiple times on the project. For some temporary structures, such as scaffolding, the structures may also be used from project-to-project. When re-used multiple times, temporary structures are exposed to loadings, environmental conditions, and work process influences which do not impact the permanent structure. These impacts include repeated loading/unloading, erection/dismantling, and exposure to environmental and worksite conditions during transportation and storage. Accurate tracking and assessment of the condition and reliability of temporary structures is a critical component of efficient utilization of temporary structures and construction safety management.
Reinforced concrete is used throughout the US on almost all construction projects. As identified by Haque and Saherwala (2004), the cost of formwork is significant and generally amounts to 40% to 60% of the cost of a reinforced concrete structure. While concrete formwork is a common type of temporary structure, only minimal literature is available that discusses and evaluates the worker activities needed to construct the formwork, the worksite conditions to which the formwork is subjected, and the design implications of the site conditions (Hallowell 2008; Hurd 2005; ASCE 2002). The lack of research in this area is especially evident in regards to the re-use of formwork. For example, the American Society of Civil Engineers (ASCE) Design Loads on Structures During Construction manual states that “The designer should be aware that temporary structures used repeatedly are subject to abuse and loss of capacity,” and that the safety factors, which correspond to the ratio of the material strength over the design load, “need to be lower than those used for ordinary strength design to compensate for this loss of capacity” (ASCE 2002). However, the ASCE manual does not provide guidance on what the lower safety factors should be.

Similarly, when considering the appropriate safety factors to apply when re-using formwork many times, the American Concrete Institute (ACI) indicates that ten form uses was discussed as the dividing line between “limited” and “considerable” re-use, but that no consensus was reached (Hurd 2005). An assessment of the combined duration of loading when the formwork is used repeatedly is essential as part of the design process for wood formwork which includes the application of an allowable stress adjustment factor based on the duration of the load. Additionally, the design process includes an adjustment factor for safety that is related to the quality of the wood material, i.e., a greater reduction in capacity is required for lower quality material. ACI indicates that the formwork designer must decide on the appropriate safety factors to use for form re-use based on the jobsite conditions (Hurd 2005). However, in many cases verifying the jobsite conditions is very difficult given the timing in which the formwork design is completed and the dynamic, fast-paced, and varied nature of the construction process.

Due to the difficulties in considering actual construction site implications in the design of formwork, and a desire to maintain a fast and efficient construction process, assessments of formwork integrity are commonly made in the field by site personnel based on subjective visual inspection. Formwork materials that are stripped following use are visually inspected and a determination is made by a construction foreman, superintendent, or other construction site personnel as to whether the formwork should be re-used. This subjective decision process may lead to overly conservative decisions (under-utilized formwork) and therefore a lack of material efficiency and increased cost. On the other hand, if the formwork capacity is over-estimated, failure of the formwork when it is loaded upon re-use may result in worker injuries and fatalities. The ability to assess formwork capacity for re-use is a critical component of efficient and safe use of formwork.

It is clear that there is a lack of quantitative knowledge and guidance related to the impacts of formwork re-use, specifically of the reliability of formwork, material efficiency, and associated risks to construction workers. Further research is needed to: (1) map the typical on-site lifecycle of formwork; (2) identify and quantify the site operations and environmental impacts to formwork use and efficiency; and (3) quantify the expected reliability and resource efficiency of formwork based on multiple re-uses in order to fill the gap in design knowledge regarding appropriate safety factors. In addition, practical guidance is needed which can be easily referenced during both design and construction, and which provides an objective assessment of the integrity of formwork materials and their suitability for re-use. This paper
presents research intended to be a first step in providing this guidance to the construction industry.

CURRENT KNOWLEDGE AND PRACTICE

Formwork materials are commonly sized and assembled into panels and then the panels are erected in the proper location and orientation. After the concrete is poured and cured, and the formwork removed, the formwork materials may be used again for another concrete pour. Throughout this process the formwork materials are exposed to repeated loadings from the concrete pressure and worker activities, and to multiple environmental loads. Many work tasks are required as part of this process. Formwork construction is an extremely common process, yet only a limited amount of literature is available that discusses the specific activities involved in the construction process. Hurd (2005) indirectly describes and defines formwork construction activities. In a study of worker safety risk related to concrete formwork activities, Hallowell (2008) identified the following general worker tasks and movements associated with concrete formwork:

- **Transport materials and equipment without motorized assistance**: Workers carrying items of varying weights such as 2x4’s, plywood, form panels, ties, adjustable pipe braces, etc. from one location to another by hand, in a wheel barrow, or in a bucket.
- **Transport materials using construction vehicle or other motorized assistance**: Materials transported by vehicles such as trucks, skid steers, forklifts, cranes or scissor lifts when the equipment is readily available or when the site is relatively large and formwork sites, mills, and material/equipment storage are spread out.
- **Lift or lower materials, form components, or equipment**: Unassisted vertical transport of construction materials, formwork components, or equipment.
- **Hold materials or components in place (static lift)**: Temporary support for a portion of the concrete form while other workers connect materials or components.
- **Accept/load/connect materials or forms from crane**: When a crane is used to transport materials or form components workers must accept the materials from the crane and/or load the crane with excess materials or waste.
- **Cut materials using circular or table saw**: Cutting materials such as 2x4’s, plywood, or aluminum members using equipment such as a circulating saw, reciprocating saw, or table saw.
- **Nail/screw/drill form components or other materials**: Nailing or screwing form components or materials using a hammer, nail gun, electric screwdriver, impact wrench, staple gun, or other basic equipment.
- **Hammer using sledgehammer or other equipment**: Hammering stakes or other components into the soil or other material (different from nailing components and materials together).
- **Plumb and/or level forms using body weight, pry bar, or other equipment**: Leveling and plumbing forms using body weight, pry bars, or other equipment to shift and adjust the formwork.
- **Ascend or descend ladder**: Operations that occur above or below grade typically require workers to ascend or descend ladders in order to reach the work site.
- **Inspect forms and construction planning**: Workers and crew leaders inspecting their work and plan for subsequent operations.
Excavation: In some situations the forming process may require excavation using appropriate equipment such as a backhoe, bulldozer, shovels, etc.

Form lubrication and preparation: Spraying form oil; spraying curing compound; setting and wetting curing blankets and setting expansion materials.

In research concerning formwork reuse and productivity, Ling and Leo (2000) performed a study on the reuse of traditional timber formwork in Singapore and hypothesized that five main factors could impact the reuse of formwork: (i) material grade and quality; (ii) worker attitude and efficiency; (iii) degree of structural design and complexity; (iv) design, fabrication, and stripping of formwork; and (v) site management issues. Out of these factors, and based on surveys of the industry in Singapore, the authors concluded that the factors that had the largest impact on formwork re-use were: (i) worker attitude and crew efficiency; and (ii) formwork stripping. The last factor is also highly related to the workers who handle the formwork and was also related to the worker attitude and efficiency. In Singapore, and at the time when this study was conducted, worker motivation was thus the main factor contributing to the number of re-uses.

Failure of concrete structures and worker injuries during construction activities related to formwork are traceable to collapse of the formwork systems. Hadipriono and Wang (1986, 1987), based on a survey of formwork collapses, showed that 74% of formwork failures occurred during concrete placement operations. However, loads on the formwork tend to decrease as the concrete gains strength and starts carrying loads. Zhang et al. (2012) performed a reliability analysis of typical steel scaffold and shoring members.

RESEARCH OBJECTIVES AND METHODS

The objectives of the research study were to map the work and material flow for the typical formwork construction process and characterize the risks associated with each stage of the process in order to determine the design and construction impacts on concrete formwork. The research included a focus on impacts related to the design of the formwork, construction site conditions, and construction operations. The following research questions were identified to plan and guide the research:

1. What are the construction activities/steps within the typical formwork construction process?
2. What are the different loadings on formwork during the construction process, and how does each of these loadings impact the formwork due to use/re-use?
3. What are examples of typical formwork failures?
4. What formwork design and construction issues/limitations commonly impact the use and re-use of formwork?
5. What is the process used to determine whether formwork should be re-used or discarded?

To answer these research questions, the researchers selected a mixed-methods approach to the research design which included targeted interviews and site observations. Both data collection activities targeted construction and manufacturing firms with offices located in the Pacific Northwest. Through industry contacts and the construction industry database available within the School of Civil and Construction Engineering at Oregon State University (OSU), the researchers identified construction contracting firms known to perform concrete work and
manufacturing firms which build and supply pre-fabricated formwork systems. The researchers contacted each firm to identify construction projects for on-site observations and personnel to interview. Based on the availability of projects with concrete work and proximity of the projects to OSU, the researchers identified eleven on-going projects to visit and observe the formwork activities. For each of the selected projects, the researchers visited the site, observed and recorded the formwork construction process, documented observed formwork loading, noted other operational impacts to the formwork and conducted interview(s) of appropriate personnel. The researchers focused on vertical formwork for the construction of concrete walls and columns, which was also the focus of the study.

In addition to visiting the sites, the researchers conducted in-person interviews of personnel on the eleven visited sites and within other construction and manufacturing firms. A total of 20 interviews were conducted. Eight workers were interviewed from one project, two workers from two projects, and one worker each was interviewed from the remaining eight projects. To assist the researchers in conducting structured interviews and ensure consistency between interviews, the researchers prepared an interview form with multiple questions. The interview questions asked for information on the following topics:

- The steps within the typical formwork construction process (e.g., transportation, storage, and preparation of the materials, assembly of the formwork panels, erection and loading of the formwork, formwork stripping, and re-configuration and re-use of the formwork)
- Examples of common formwork failures
- The perceived impacts of various factors on the use and re-use of formwork including construction loading, workers climbing on the formwork, assembly, removal, material qualities (warping, cracks, surface damage, etc.), and environmental conditions (rain, wind, etc.)
- Design and construction issues commonly found in formwork
- The process used to determine whether formwork should be re-used or discarded

The interview responses were recorded for analysis along with the site observations. These sets of data were combined to develop a map of the lifecycle of formwork on construction sites using value stream mapping. The researchers specified that the indicators of value for the map were to be comprised of formwork capacity/integrity (e.g., strength, stiffness, and surface texture), safety risk, and reliability. For each step of the formwork lifecycle, the common activities of construction carpenters were also identified. In each step, both a demand model (concrete loading, worker loading, environmental loading) and a capacity model are defined. Information regarding the factors that influence the condition and usability of formwork (for example: types of loading, design, conditions of transportation and storage, method of assembly, deterioration, duration of concrete curing, stripping of formwork, and exposure of components) are utilized. The information for the analysis is that collected from the construction project sites visits and interviews. The lifecycle map is used to identify the governing factors and the degree to which each factor affects formwork system performance and efficiency.

RESULTS

Based on the site visits and interviews, the researchers prepared a workflow model of the construction process for vertical formwork (Figure 1). The model includes the following major steps for the construction process: assembly, erection, pouring, stripping, reconfiguring or
dismantling, and cleaning. The design stage is not shown in the flowchart below because typically the design is prepared before the formwork reaches the site. However, occasionally and especially for larger projects, the formwork is re-designed prior to assembling the formwork. The workflow shown in Figure 1 is the result of both literature review and interviews performed at various sites. Even though this workflow is generic, overall it corresponds to what was observed at an ongoing construction site of a four-story building in the Pacific Northwest.

The interviews of site personnel provided useful information about formwork exposures, construction techniques, and factors affecting worker safety. The interviews were conducted on eleven ongoing construction projects with a total of 20 participants. On these projects, self-owned plywood formwork assembled on site was used. The formwork was mainly stored outdoors, exposed to the surrounding temperature, moisture, and rain conditions (all which were tracked), and the loads from workers and other panels overlaid or other materials stored on each panel while in storage.

From the survey, in terms of safety issues, most project team members did not pinpoint any specific issue. When deciding whether the plywood could be re-used or should be replaced, most project team members agreed that the most common problem is the degradation of the corners and edges of the plywood. In addition, those interviewed stated that the replacement of the plywood is based on on-site observation of the panels, mainly related to the visual aspects of the formwork and its future use.

![Workflow Model of Formwork Construction Process](image)

**Figure 1. Workflow Model of Formwork Construction Process**

**Model Verification**

On-site observations were carried out at a selected project to obtain and validate the formwork use cycle. The selected project is a four-story, concrete frame-wall building with a
total floor area of approximately 100,000 square feet, and a total cost of $55 million. For the purpose of this research study, only the formwork for the vertical shear walls in the project were under observation.

The researchers observed the erection of formwork for the construction of nine concrete walls per story. Figure 2 shows a site plan containing the building and the location of the concrete walls. In Figure 2, the walls are identified as W1 to W9. For the nine walls, the subcontractor assembled four different formwork sets (S1 to S4 in Figure 2), each composed by two panels that went through several erection cycles on each story. Figure 2 also shows which sets were used to form which walls. For example, in the construction of Wall #9 (W9), sets 3 and 4 (S3 and S4, respectively) were used in alternate floors. The observed activity flow that was used to verify the model illustrated in Figure 1 is described below (the steps identified correspond to those shown in Figure 1):

1. The panels were pre-assembled and transported to the site (step #1).
2. Once on site, the panels were stored on a temporary inventory (step #2).
3. From the temporary inventory the first panel was moved and either erected (step #5) or stored closer to the place where it was to be erected (step #4), and then moved again (step #3) to finally be erected (step #5).
4. Once the first panel of the wall set was up, the crew assembled the rebar (step #6).
5. The second panel of the wall set was then moved and was either erected (step #7) or stored closer to the place where it was to be erected (step #4) and then moved again (step #3) to finally be erected (step #7).
6. Once both panels were erected, the concrete was poured and cured (step #8).
7. The walls were then stripped (step #9) and each panel moved (step #10) to another temporary inventory (step #11).
8. If needed, the panels were reconfigured (step #12) and then cleaned (step #13). Otherwise, the panels were cleaned (step #13) and then stored in temporary inventory (step #14) until the start of a new cycle with step #3.

![Figure 2. Site plan and example of movement on site for a wall formwork set](image-url)
9. After the last cycle, the panels were dismantled (step #15) and the plywood sheets and metal framing members stored (step #16).

10. Finally, the plywood sheets were either cleaned (step #17) and transported off-site (step #19) or scrapped (step #18) and then transported off-site.

The various use cycles of formwork were observed, and modifications to the general formwork use cycle were made based on the observations. It is to be noted that almost each observed formwork cycle was unique in the fact that all steps in the general formwork cycle were not included in each cycle, and no cycle was identical to the other. For example, on some floors, the formwork set S3/S4 used concrete walls W8 and W9 (shown in Figure 2) were stripped, moved and erected on the same day without stockpiling and cleaning, thus speeding up the process and skipping a few of the steps in the general model shown in Figure 1 or performing any assembly. Thus, even though the model in Figure 1 is generic, it was noted that specially between the stripping and re-use of the formwork, several options are possible.

For each of the 19 steps in each cycle, information related to the issues observed on site was collected by the researchers. An example of the information collected, which is related to safety issues and loading on formwork, is shown in Table 1. In Table 1, information is only listed for two steps (step #8 and #9) of one of the re-use cycles (cycle 4 shown in Figure 2) and for set S3.

### Table 1. Example of on-site observed issues

<table>
<thead>
<tr>
<th>Step #</th>
<th>Description</th>
<th>Safety Issues</th>
<th>Loading on formwork</th>
</tr>
</thead>
</table>
|        | Concrete pour and cure | • Repetitive motion  
• Use of bodyweight to move and lead concrete pump hose  
• Climb over the formwork  
• Exposure to harmful substances  
• Fall to lower level  
• Ascend and descend ladders and structure | • Concrete  
• Workers on the panels  
• External and Internal Vibration  
• Environmental Loads- Wind, Rain etc. |
|        | Stripping | • Repetitive motion  
• Falling objects  
• Struck-by panels  
• Use of bodyweight to move and lead formwork while being lifted by the crane  
• Ascend and descend ladders and structure | • Workers on the panels  
• Twisting of panels to detach from concrete  
• Prying of corners  
• Drag the bottom part of the panel on the concrete before lifting the panel  
• Hammering  
• Ripping |

Figure 3 presents examples of observed activities and damage. Figure 3a shows a crewmember holding the concrete pump hose in place during the wall pour. Figure 3b shows crewmembers climbing up a ladder and the formwork to vibrate the concrete after pour. During this climbing operation it can be seen that no harnesses were used by the workers which was
typical during ascending and descending activities. Figure 3c shows a crewmember using his bodyweight to help secure the formwork panel while stripping the wall. Finally, Figure 3d illustrates damage observed after panel stripping. Whenever possible, visual inspection also allowed for estimation of the percentage of damage at the end of each cycle and activity.

To complement the visual assessment and understand how the erection cycles affect the capacity of the plywood, samples of the plywood panels were collected after each pour. As part of the on-going research, the plywood samples will be tested in the Wood Science Laboratory at OSU to determine strength and stiffness degradation. Figure 4 shows markings on panels for tracking the panels on the site. Also, the markings allow the researchers to keep track of the location of the plywood sheet within each panel (Figure 4a) and the number of reuses and date of pour (Figure 4b).

![Figure 3](image1.png)

**Figure 3.** Example of observation of on-site operations and observed damage

**CONCLUSIONS AND RECOMMENDATIONS**

The main findings from these preliminary research efforts were a clear picture of the different formwork techniques being employed on various construction sites, development of the typical formwork flowchart on a project, and realization of the need to gather data on the workers’ perspective on safety issues related to the use and re-use of formwork. Site observations verified some of the results of the interviews and allowed for fine-tuning of the mapped workflow. However, several safety issues were identified and a few sample issues are identified herein. The mapped workflow is used to identify the number of re-uses of each
formwork set, as well as the number of re-uses of each plyform sheet within each panel. For each step of the workflow safety issues were identified and exposures (loads and environmental conditions) were observed and when possible quantified. Further research efforts are being undertaken to quantify the impacts of formwork re-use, and the site conditions and operations, on the integrity of the formwork.

![Figure 4. Sample panel identification](image)

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