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Use and Re-use of Formwork: Safety Risks and Reliability Assessment

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CPWR Small Study Report

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Use and Re-use of Formwork: Safety Risks and Reliability Assessment

(CPWR Small Study No. 13-2-PS)

FINAL REPORT

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Drs. Gambatese and Barbosa along with research assistants mapped the lifecycle of vertical concrete formwork on three construction sites, and identified and evaluated the typical site environmental and operations impacts on formwork during its use and re-use. The researchers collected formwork samples that experienced different levels of re-use and conducted laboratory tests to determine the extent to which re-use affects the structural capacity of formwork and the safety of those constructing the formwork. The researchers utilized the test data, along with responses from worker risk perception surveys and 438 OSHA fatality report summaries related to formwork, to assess the safety risk associated with formwork construction and the reliability of formwork designs to safely withstand repeated re-use.

Key Findings:

- The general site lifecycle of vertical concrete formwork includes up to 18 steps that include a combination of: moving, stockpiling, and preparing materials; assembling and erecting formwork panels; panel loading (concrete pour); formwork stripping; visual inspection; cleaning; and dismantling/re-using.
- Workers who construct formwork identify formwork erection, stripping, and assembly as the activities that contribute the most to the cumulative risk in the formwork lifecycle. In addition, sensitivity analyses of the perceived unit risk indicate that low-frequency, high-severity incidents have the greatest impact on the risk.
- The most prevalent formwork activities associated with construction worker fatalities that are described in the OSHA Fatality and Catastrophe Summaries related to formwork are: concrete pouring, formwork erection, and formwork stripping.
- Reliability assessment results are mixed due to uncertainties in actual formwork loading on the site and inconsistent design guidance. The uncertainty is mainly due to inherent randomness in the material properties and in the influence of exposure of the concrete on the strength of the concrete form panels (plyform).
- High levels of loading on formwork with no resulting failure appear to be related to overly simplified and over-conservative design equations that are currently prescribed in design guides.

Original Project Abstract:

The construction and placement of temporary formwork for casting concrete continues to be a high risk activity, especially in regards to fall injuries and fatalities. Falls may occur as a result of the formwork collapsing under extreme and repetitive loading conditions experienced on the construction sites. A need for research in this area is especially evident in regards to the re-use of formwork. The ASCE *Design Loads on Structures During Construction* manual indicates that formwork designers need to be "aware that temporary structures used repeatedly are and that safety factors "need to be lower than those used for ordinary strength design to compensate for this loss of capacity." 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, ACI indicates that ten form uses was discussed as the dividing line between "limited" and "considerable" re-use, but that no consensus was reached since this value is not based on any formal research data. In addition, data collected in the present research study does not indicate that the ten (10) re-uses has scientific or empirical support.

It is clear that there is a lack of quantitative knowledge of the impacts of re-using formwork, specifically of the reliability of formwork and associated risks to construction workers. To help guide formwork design and improve formwork reliability, the proposed research includes:

- mapping the typical on-site lifecycle of formwork;
- identifying and quantifying the site operations and environmental impacts to formwork; and
- quantifying the expected reliability of formwork based on multiple re-uses.

The research involves visiting multiple construction sites to observe and record the formwork construction, erection, loading, and stripping process, and determine the site conditions and loadings to which the formwork is exposed. Formwork components are then collected after multiple uses and tested in the lab to evaluate their deterioration and loss of capacity. The site and laboratory data are then used to evaluate the risk and reliability of formwork after multiple uses. The research output is expected to be knowledge about formwork re-use which can be used to modify the formwork design manuals if appropriate.

Use and Re-use of Formwork: Safety Risks and Reliability Assessment

• 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. The use and re-use of concrete formwork exposes the workers involved in formwork use to different types of injury. This research study aims to: (i) map a general site activity workflow for the use and re-use of vertical formwork; (ii) evaluate onsite safety risks associated with formwork use and re-use activities; and (iii) assess the reliability associated with formwork use and re-use.

Development of the mapped workflow and identification of safety risks associated with each activity were based on interviews of construction site foremen involved in formwork construction and jobsite observations of formwork construction activities. Based on results from a survey of 32 carpenters engaged in concrete work, worker risk associated with formwork activities was quantified. Erection, stripping, and assembly of formwork were found to be activities that contribute most to the cumulative risk. Worker perception of the safety risk was compared to the recorded Occupational Safety and Health Administration (OSHA) Fatality and Catastrophe Summaries. Data collected from OSHA injury reports indicate that concrete pouring, erection, and stripping are the activities with the highest risk. This result reveals a notable disconnect between the survey-based worker perception results and corresponding OSHA statistics. Sensitivity analyses of unit risk based on worker perception indicate that high severity incidents have the greatest impact on the risk.

Reliability assessments were performed by comparing the capacity of formwork samples with different numbers of uses to the estimated load demand. The reliability assessment results were mixed as a result of uncertainty in the computation of the sample loading and capacity and overly conservative design guides which were identified during the study. High levels of loading on the formwork with no resulting failure appears to be related to overly simplified and over conservative design equations that are currently prescribed in design guides. The uncertainty is mainly due to inherent randomness in the material properties and value of the applied concrete loading on the concrete form panels (plyform). It is recommended that further study be conducted that employs different tests of capacity assessments and includes the actual load demand on the formwork by measuring loads on the project site.

• Introduction

Formwork has been used widely in construction practice since the discovery and establishment of Portland cement concrete as a favored building material. Formwork is a temporary structure that can be incorporated into the permanent structure or removed after the concrete has reached design strength. Formwork costs can constitute from 35 to 60 percent of the concrete cost on projects involving large quantities of concrete work (Hurd 2005; Lab 2007).

There are many types of formwork available in the market for use depending on the application and location of use. The two most common types of formwork are traditional site-built timber formwork and engineered formwork systems. The former is the more labor and time intensive of the two, especially for projects with a large amount of concrete work. However, traditional timber formwork is also the most flexible out of all the different types of formwork and hence can be used to form sections with intricate architectural detail. Traditional timber formwork typically consists of plywood or timber sheathing, with timber members placed as studs and wales on the back of the formwork. Falsework, such as braces or shoring, may be used depending on the concrete member being formed. Engineered formwork is commonly used due to its relative ease and speed of assembly. Engineered formwork systems consist of formwork panels with plywood or metal sheathing on an aluminum or steel frame, and can be connected with pins, clamps, or screws. These prefabricated systems also have the additional advantage of lower overall cost and larger number of uses compared to traditional timber formwork.

Formwork is generally designed according to guidelines set by various associations or publications such as the American Plywood Association (APA), *National Design Specification for Wood Construction* (AWC, 2005), and ASCE *Design Loads on Structures During Construction* manual (ASCE 2002). Perusal of the more commonly available guidelines indicate that re-use of formwork is generally not formally factored into the design of formwork. Formwork is subjected to a wide variety of loads and exposures when in use, and it stands to reason that there would be a reduction in the strength or structural capacity of the formwork as it undergoes multiple uses. Reliability and risk related to formwork activities are also topics that are underexplored. Use of formwork often involves working at heights, and on temporary platforms, which are factors that affect the efficiency and safety of construction workers. In addition, activities such as stripping of formwork from concrete and assembling forms on site create a certain amount of risk to the workers. The location of the activity and the activity itself affects the productivity of the worker as well as the safety of the worker. These effects need consideration during design and by regulatory agencies such as OSHA. Most safety issues such as fall protection, scaffolding, and use of power tools, have been addressed in the OSHA standards for construction (29 CFR 1926) by themselves. However, these issues need further investigation from the perspective of formwork use. OSHA Fatality and Catastrophe Investigation Summaries give an idea of the various types of incidents associated with concrete formwork, as well as the causes of incidents associated with formwork use. There are no mandatory rules regarding the use and re-use of formwork, but just guidelines for use.

It can be seen from pertinent literature that existing formwork design guidelines do not provide all of the necessary information required. For example, the *Design Loads on Structures During Construction* (ASCE, 2002) manual states that, "The designer should be aware that temporary structures used repeatedly are subject to abuse and loss of capacity,"… and safety factors "need to be lower than those used for ordinary strength design", while providing no guidelines for assessing the loss of capacity. The *Guide to Formwork for Concrete* (ACI 347, 2004) indicates different design criteria for "limited" and "considerable" re-use, but no method of differentiating between limited and considerable re-use is specified. The *Concrete Forming- Design/Construction Guide* (APA, 2012) utilizes an "experience" adjustment in its formwork design guide to account for concrete setting; however, there is no explanation where this value comes from.

A research study was conducted by OSU on formwork use and re-use as a step forward in providing some of the details missing in the literature examples mentioned above. The research study was supported by CPWR through NIOSH cooperative agreement OH009762. Its contents are solely the responsibility of the author and do not necessarily represent the official views of CPWR or NIOSH. This document is the final report of the aforementioned study. Further details are provided in the student researcher's thesis titled, "Risk and Reliability related to Use and Reuse of Formwork".

- ## Research Objectives

Three primary objectives (POs) and five secondary objectives (SOs) were established for this study. The POs are designed to expand the general understanding of formwork use, as well as the associated risk and reliability in formwork use and re-use. The SOs were created to guide the research in attaining the POs. The POs and corresponding SOs are:

PO #1 - Map the typical use cycle of formwork on-site

SO #1 - Establish a sequence of activities that represent an overall formwork cycle

SO #2 - Determine the main factors that impact formwork lifecycle on a project

PO #2 - Identify the primary factors contributing to risks associated with the use and re-use of formwork and evaluate the risks posed to the workers caused by the execution of various activities that comprise the formwork cycle

SO #3 - Identify the major causes of incidents related to formwork

SO #4 - Quantify risk associated with each activity in the established formwork cycle

PO #3 - Evaluate the structural reliability associated with formwork use and re-use

SO #5 - Evaluate the change in strength characteristics of formwork between uses

Due to the nature of the SOs established, it was necessary to carry out research using multiple methods. The relationship between the different objectives and associated research methods is represented in Figure 1. The following list summarizes the methods used to meet each of the SOs:

- SO #1 and SO #2: A combination of observation, interview, and survey methods of research was deemed the most suitable. Initially, on-site interviews were carried out in order to obtain and establish the standard procedures of formwork use, and determine factors impacting the formwork lifecycle. Based on these results, on-site monitoring of formwork was carried out and a sequence of activities representing the workflow of a general formwork use cycle was obtained. Further, based on this general mapped workflow, project specific mapped workflows can be established.
- SO #3 involved review and text recognition of features in the OSHA Fatality and Catastrophe Investigation Summaries to identify the main causes of past incidents related to formwork.
- SO #4 was met using a safety survey of construction workers who install formwork.
- SO #5 was met by obtaining formwork samples from selected construction projects with concrete work and testing the samples in the lab to determine the impacts of re-use and site exposure.

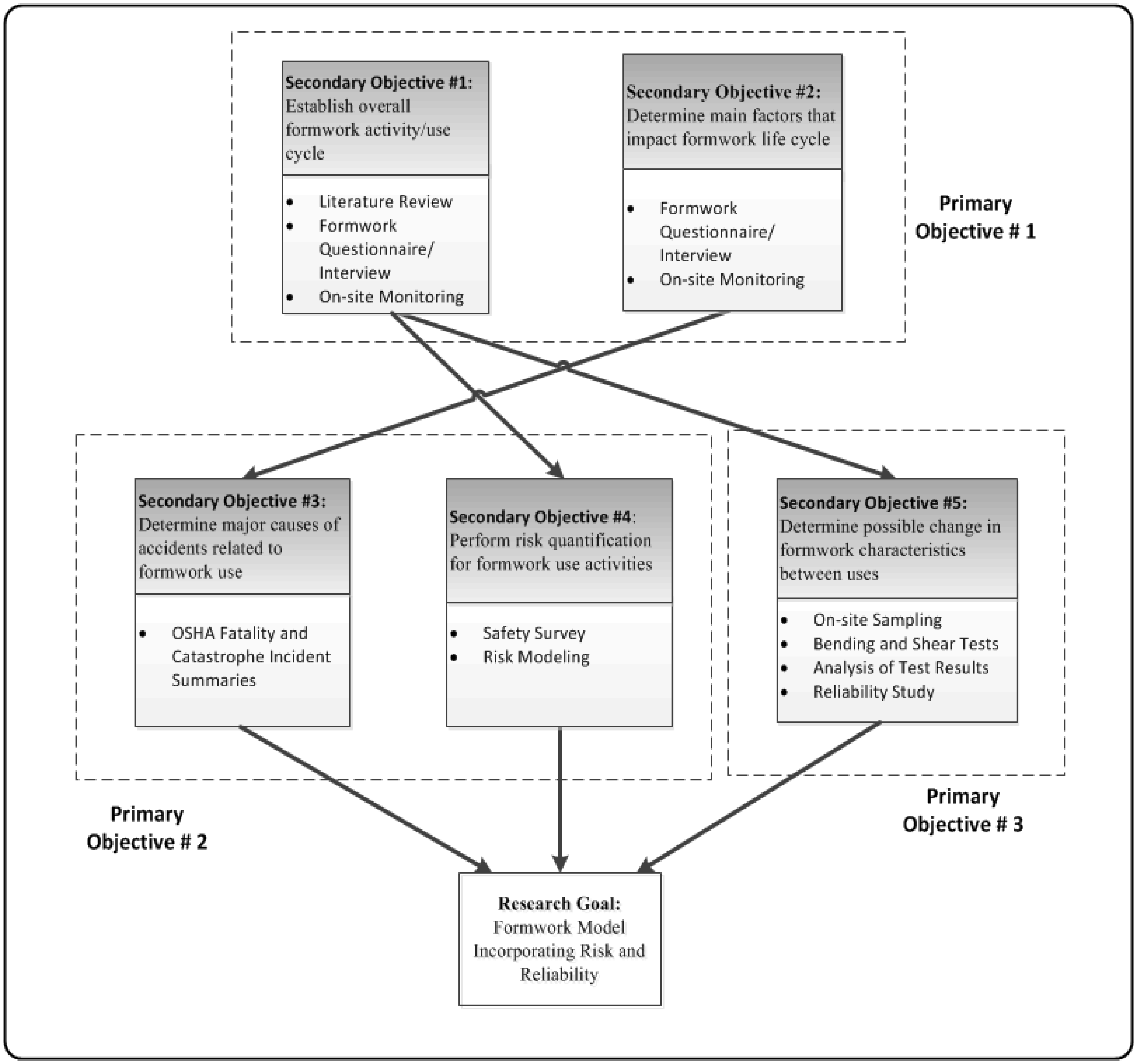

Figure 1: Research Scheme

- **Research Methods**

As the first step in identifying factors that impact the lifecycle of formwork, two methods of formwork monitoring were implemented: (i) a formwork questionnaire, to be answered in an interview format, and (ii) on-site tracking of formwork, which was to be conducted after identifying the most important criteria considered by construction personnel pertaining to re-use. To identify the various activities associated with the formwork cycle in detail, a questionnaire was developed and used for conducting interviews of formwork construction personnel. The purpose of the questionnaire was to obtain information and record observations pertaining to formwork activities and formwork use, as well as to identify the criteria used to determine the re-usability of formwork components on real-time projects. This effort was regarded as a preliminary attempt at obtaining the various stages of use in the formwork cycle. Twenty responses in total were collected from various construction personnel working on projects in Oregon and Washington. The respondents consisted of superintendents, project engineers, and foremen. For onsite monitoring, three projects using traditional timber vertical formwork were identified. The projects were all in the same region so as to maintain constant accessibility by the research team to the project site throughout the duration of the concrete construction activities. On each project, the research team gained access to the project site, regularly observed the movement and use of formwork, and maintained photographic records of many formwork use cycles that occurred during the project. Any potential safety issues and additional impacts to formwork were noted.

In order to assess worker safety risks associated with formwork and obtain an idea of the typical causes of injuries associated with formwork, the researchers collected and analyzed data from the publically available OSHA Fatality and Catastrophe Investigation Summaries. In the list of workplace injuries, illnesses, and fatalities available on the OSHA recordable incident database, 438 cases associated in some way with concrete formwork from 1984 to 2012 were found using a keyword search of the database. All 438 case summaries were reviewed to understand the proportion of risk associated with each activity in the formwork cycle, and further categorized according to the activity performed by the worker at the time of the incident and the severity level of the incident. A detailed statistical summary of the number of incidents can be seen in the Results and Key Findings section of this report.

To measure the possible deterioration in the structural capacity of formwork, and thus, assess the reliability of the same, formwork samples were collected from the three projects monitored. To compare the strength between each use, efforts were made to obtain samples of formwork which had undergone different numbers of uses. Each number of uses was considered one treatment. An unused sample was also collected from each project so as to have a basis of comparison to the used samples. Unused samples collected for each project were consistent with those used in the project. For this study, samples of only the plywood sheathing were collected, rather than an entire form panel. This was done so as to maintain constant test sample dimensions and also to ensure that the same number of identical test specimens were tested from each treatment.

To assess the possible change in bending capacity between different numbers of uses, Method B: Two-point Flexure Test of ASTM D3043 was chosen. Method B, otherwise referred to as third point bending test was chosen for testing the samples to obtain the bending capacity, provided that the specimen length is controlled. To assess the possible change in rolling shear capacity between different numbers of uses, Method B prescribed in ASTM D2718 – Standard Test Methods for Structural Panels in Planar Shear (Rolling Shear) was used. Method B: Planar Shear induced by five-point bending was chosen given that in this research, the specimen size is dictated largely by the availability of sample panels and the loading of vertical formwork is applied perpendicular to the face of the plywood sheathing.

For the worker survey, the participants targeted were workers who have hands-on experience in the use of formwork, and hence are exposed to the various safety risks and hazards associated with formwork usage. Possible respondents were approached in two ways: first, by going to project sites with concrete construction and obtaining permission from the Project Engineer/Foreman to obtain survey responses, and second, by attending the Pacific Northwest Regional Council of Carpenters (PNRCC) meetings and asking the attendees to fill out survey questionnaires. Responses were gathered from four different gatherings. Two gatherings consisted of groups of workers at two project sites organized specifically to obtain survey responses, and the other two were monthly PNRCC meetings. Access to and availability of workers to participate in the survey varied between project sites. As a result, this limited the number of sites on which the surveys could be administered to two sites. Furthermore, questionnaires completed by workers at the PNRCC meetings provided information from multiple workers in the region, which provided more useful information since typically workers may be on a specific site for only a short duration (weeks) and therefore difficult to access. The participants were provided with initial information about the research study, and also about the severity levels of incidents and the frequency scale values. The frequency scale values adopted, and used in the survey questionnaire, are described in

Table 1 (Dharmapalan, 2011):

Table 1: Frequency Scale Values

Frequency Scale Value	Original Range	Worker Hours/ Incident	Incidents/Worker Hour
10	1 hour	1	1.000000
9	1 day	9	0.111111
8	1 week	45	0.022222
7	1 month	189	0.005291
6	6 months	1134	0.000882
5	1 year	2250	0.000444
4	5 years	11250	0.000089
3	10 years	22500	0.000044
2	50 years	112500	0.000009
1,0	Negligible	0	0

Following the classification of consequence model described in Dharmapalan (2011), the four severity levels used for the present study are:

i. Near Miss: No impact on work time, and no or negligible injuries sustained. Assigned a severity value = 1.

ii. Low Severity: Temporary and/or persistent discomfort and pain, requiring minor first aid. Assigned a severity value = 17.

iii. Medium Severity: Required major first aid or medical attention, and loses more than one work day. Assigned a severity value = 158.

iv. High Severity: Incident resulted in death or permanent disability, and worker could not return to work in the same capacity. Assigned a severity value = 14,282.

The severity values assigned to each severity level that are shown above were developed by Dharmapalan (2011) based on work by Hallowell (2008). Literature on severity scales suggests both linear and geometric scales for the range of incidents from near miss to fatality. Hallowell utilized a geometric scale across 10 severity categories, ranging from a severity value of 1 for negligible severity to a severity value of 26,214 for a fatality. Using a geometric scale, there is a large increase in severity values for the more severe injuries. For example, the change from lost work time injury to permanent disablement is a factor of 4, and the increase from permanent disablement and fatality is a factor of 256. The research by Dharmapalan and the present research, however, utilize only four severity categories as listed above. Therefore the severity values needed to be modified to account for fewer severity categories. To obtain severity values for just the four categories, Dharmapalan used a weighted averages approach based on the values developed by Hallowell. Further detail on the development of the severity values is available in the cited documents.

The rounded mean/median frequency value and activity exposure value are calculated from all the survey responses received. The risk value for each activity is then calculated. The risk for each activity is calculated from the rounded mean/median frequency values for severity using the following equations:

$$\text{Total Unit Risk} = \sum (\text{Frequency} \times \text{Severity})$$

$$\text{Cumulative Risk} = \sum (\text{Exposure} \times \text{Frequency} \times \text{Severity})$$

In the above formulas, the frequency is taken from the scale in

Table 1, the severity values come from the list shown above, and exposure is the percent of time a worker spends performing each activity as indicated by the workers in the survey responses.

The theory of structural reliability can also be used for comparing risks. That is, risk can have two components: demand and capacity. When the risk is formulated in this way, the structural reliability is a component that appears in all steps, but mainly in the activity associated with casting of concrete. The total risk thus accounts for worker safety as well as structural reliability of the panels.

To understand and quantify the structural safety associated with formwork use, the reliability index, which is a safety index formulation, is employed (Novak & Collins, 2013). For the calculation of a reliability index, the resistance (or the moment carrying capacity), R, and the applied load (or the demand) Q, are required. Here, the capacity R is determined from the test data obtained from various uses and the demand Q is obtained from the design guidelines set forth in *Formwork for Concrete* (Hurd, 2005). It is assumed that R and Q are normally distributed random variables, and that these are statistically independent. The standard deviation and mean of the capacity R are calculated from the various test specimens, while the variation in the demand Q is calculated using the standard deviation and mean of the concrete unit weight, obtained from literature (Ellingwood, Gambolos, MacGregor, & Cornell, 1980). The reliability index is calculated according to the following equation (Novak & Collins, 2013):

$$\text{Reliability Index, } \beta = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^2 + \sigma_Q^2}}$$

where: μ_R = mean of capacity, R

μ_Q = mean of demand, Q

σ_R = standard deviation of capacity, R

σ_Q = standard deviation of capacity, Q

The reliability index is related to the probability of failure as follows, where P_f is probability of failure, and ϕ denotes a cumulative distribution function (CDF):

$$\beta = -\phi^{-1}(P_f), \text{ or } P_f = \phi(-\beta)$$

Thus, it can be seen that the higher the value of the reliability index, the lower is the probability of failure.

Detailed descriptions of the various methodologies employed, the literature reviewed to decide upon the various methodologies, and the results can be found in the student researcher's Master's thesis, titled "Risk and Reliability Associated with Use and Reuse of Vertical Formwork" (Dharmapalan 2011).

• Results and Key Findings

1. Mapped Workflow for General Formwork Use

A workflow was mapped based on the formwork handling activities observed on various projects and the 20 responses to the formwork questionnaire. The workflow map is shown in Figure 2. The mapped workflow obtained for general formwork use can be tailored to fit formwork use on any project by eliminating the steps not performed at the particular project site.

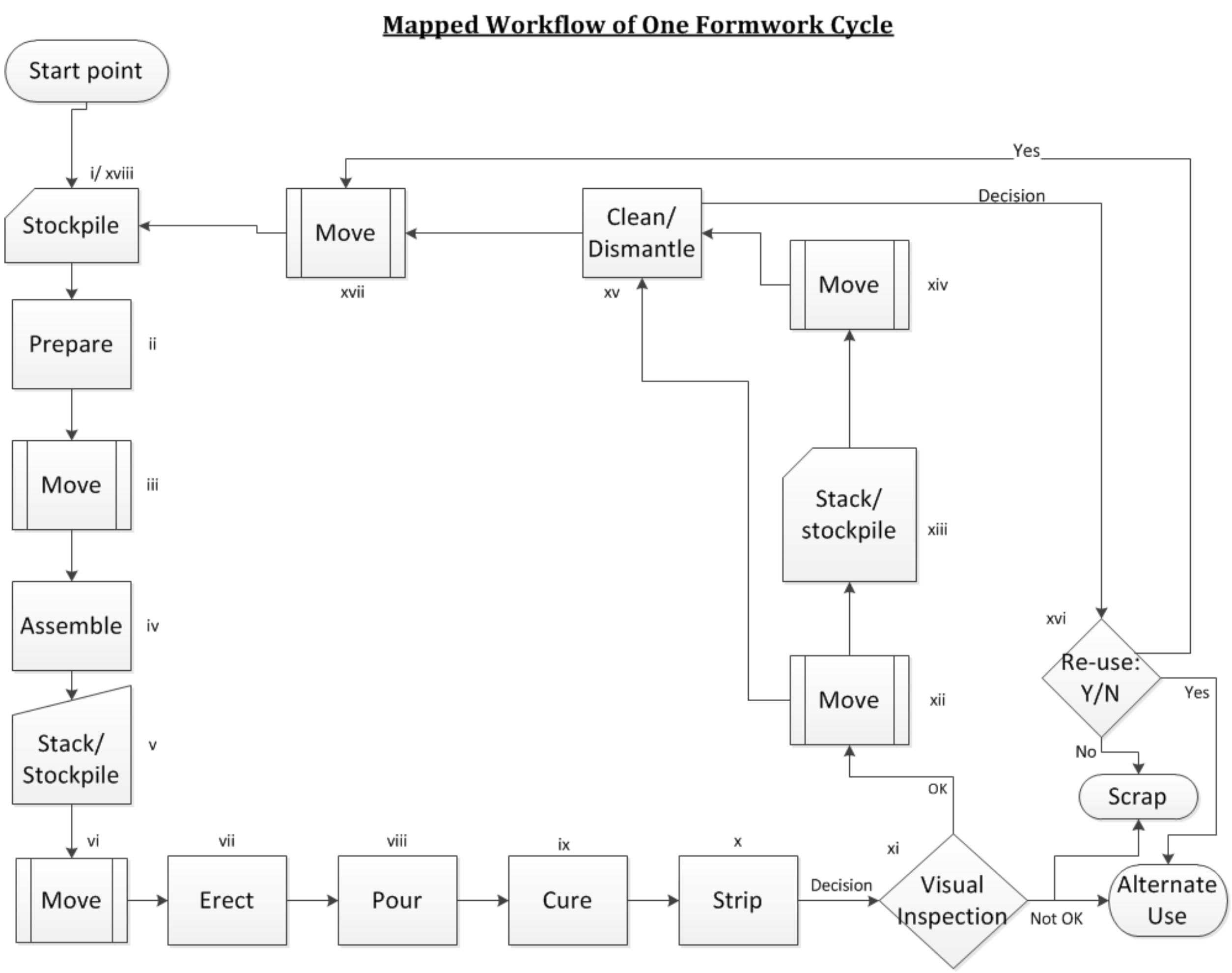

Figure 2: Mapped Workflow for One General Formwork Use Cycle

One general cycle of formwork use consists of the following steps:

i. Stockpile – When different formwork components are transported to a project site, they are stored someplace on the project site by stacking them according to size, material type or other relevant criteria. Storage on site is typically done outdoors on pallets, and is stored uncovered.
ii. Prepare – In this step, the components are taken to a designated work area and cut to the dimensions desired to construct formwork as per project specifications.
iii. Move – This is an optional step, where the prepared components may or may not be moved elsewhere for assembly, or for assembly at a later date.
iv. Assemble – The prepared components are assembled into formwork panels using various connectors, such as nails, bolts, and clamps, driven by hand or by other mechanical means.
v. Stack/Stockpile – This is an optional step, where the assembled formwork panels may be stockpiled on site for use after site preparation.
vi. Move – In this step, the assembled formwork panels are moved to a different spot on the project site for erection at the point of use.
vii. Erect – For wall or column forms, the assembled formwork panels are raised into position around the reinforcing bars by hand (handset), forklift, crane, or other means and fixed in place. For wall formwork, the opposing side of the formwork is placed next, and the two panels are connected using ties. For columns, the panels on adjacent sides are placed, and the forms are fixed using bands, clamps, or other means of connection. Braces, stakes and any other necessary falsework for support are also installed.
viii. Pour – Concrete is poured into the constructed form, and vibrated internally or externally to consolidate the concrete.
ix. Cure – The concrete is left under ambient conditions of temperature and moisture to attain design strength.
x. Stripping – The stripping or striking of the formwork refers to the process of removal of the forms from the concrete after the concrete has attained the strength to carry its own weight. This process can be done by hand, or by mechanical means such as hydraulic jacks, forklifts, or cranes.

- xi. Visual Inspection – The condition of the formwork is assessed by visual inspection, and the decision is made whether to use the formwork again, or not. If the decision is no, the formwork panel is disposed of into scrap, or put to an alternate use (not as formwork).
- xii. Move – This is an optional step, where the formwork panels to be reused are moved.
- xiii. Stack/Stockpile – In this step, the formwork panels fit for re-use are stored until the next instance of use or for cleaning/dismantling.
- xiv. Move – This is an optional step, required only if the formwork has to be moved to a different spot for cleaning.
- xv. Clean/Dismantle – The formwork panels are cleaned of the residual concrete and/or any other debris that may have accumulated, and oiled. Upon cleaning, further defects present on the formwork may be revealed. Otherwise, if the use of the panels on the particular project is over, they are dismantled for storage and transportation.
- xvi. Decision to Re-use – The cleaned formwork panels are assessed again visually, to confirm that all components are sound and can produce the required surface finish. If any components are found unsuitable, they are replaced, and put into the scrap pile or to alternate uses.
- xvii. Move – This is an optional step, where the panels can be moved elsewhere due to limited availability of space on the project site.
- xviii. Stockpile – The cleaned panels are put aside till the next scheduled pour.

The endpoints of formwork materials that are no longer fit for use as formwork are either scrap or alternate use. Materials that are scrapped are not used anywhere else on the project and are placed in the waste bin or recycling bin. Those materials that are kept for alternate use may be reconfigured for use as ramps, barriers, or a variety of other needs on the project.

It should be noted that it is not necessary for all steps explained above to be present in every formwork cycle. This general cycle can be modified to fit the formwork use cycle on any project and for any type of formwork by simply removing the steps that are not performed on the particular project.

2. Validation of Mapped Workflow

The obtained mapped workflow for general formwork use was validated on three separate projects chosen for onsite monitoring. Mapped workflows were created for the timber/handset formwork observed in each of the three projects monitored. For these project-specific workflows (described below), each figure has multiple formwork cycles depicted in it.

Figure 3 shows all the different formwork cycles observed during the course of Project 1. Any of the paths as set forth in the direction of the arrows can constitute one formwork cycle. For example, after erection, pouring, curing, and stripping, visual inspection is done, and if any part of the formwork panel requires replacement, the parts would be replaced and the panel cleaned and oiled. The cleaned panel may be erected immediately for the next use, or may be stockpiled somewhere on the site depending on the progress of work, and scheduled time of the next concrete pour. While the mapped workflow in Figure 2 shows one use cycle of formwork with all possible steps, Figure 3 shows the multiple workflows observed in Project 1, with the steps not required in the project removed.

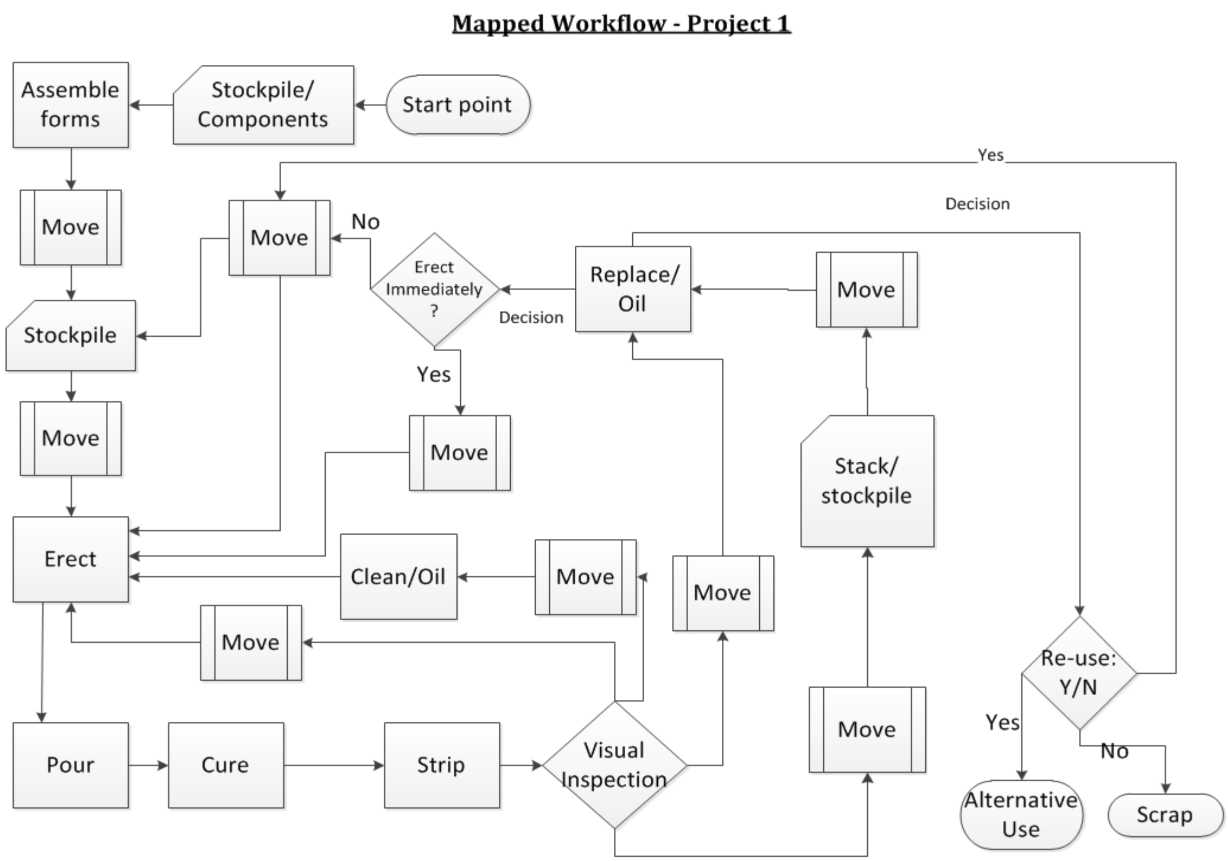

Figure 3: Mapped Workflows in Project 1

The second project monitored had a very limited number of handset forms, and most were used for foundations. The stockpiled form components were pre-prepared and assembled when the day of pour was close, and erected immediately. After the concrete was poured and cured, the foundation forms were stripped the next day by hand, and forms from foundations of similar dimensions were taken to the next spot, cleaned and oiled, and erected for the next pour. There were three different types of formwork observed on this project, but the workflow for the project (Figure 4) shows only the formwork cycles undergone by the handset wooden formwork. For mapping out the work flow, the other types of formwork used on the project were not taken into account.

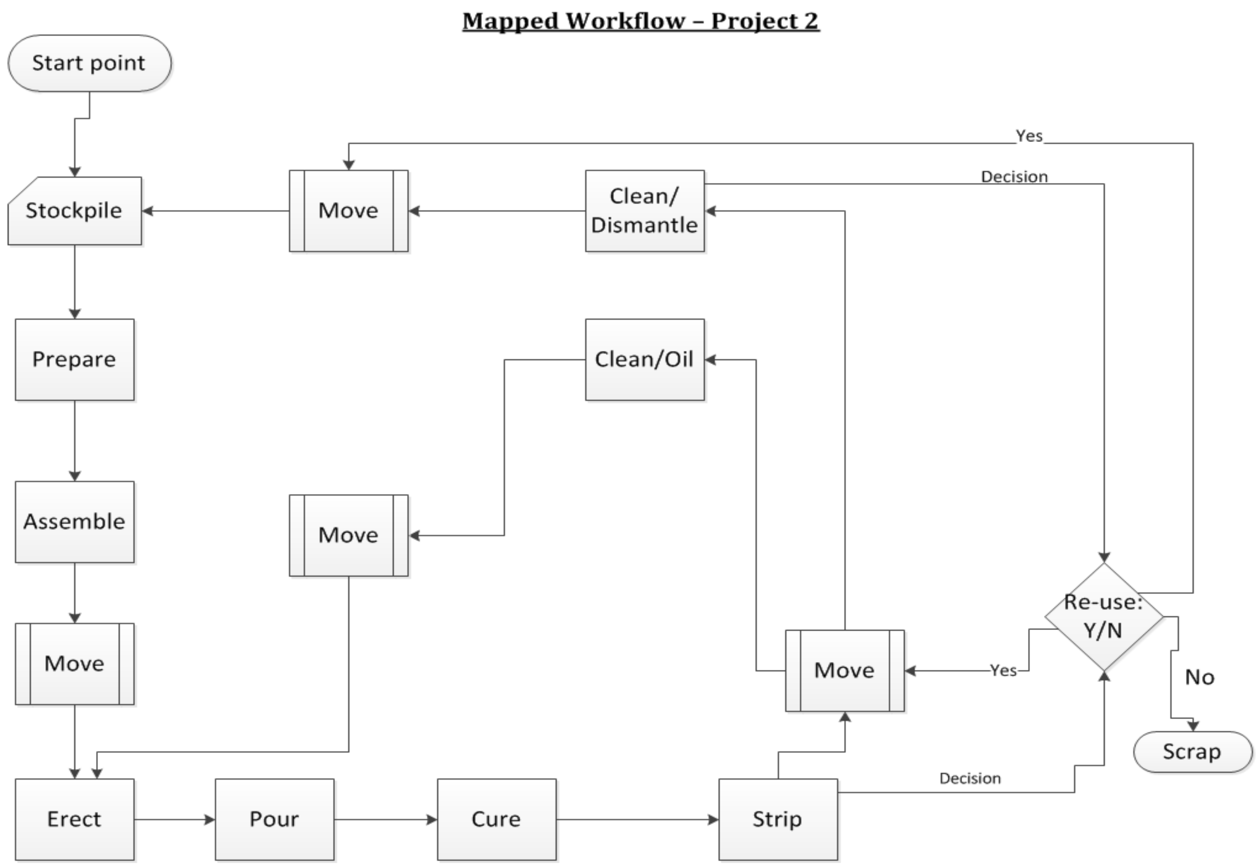

Figure 4: Mapped Workflows in Project 2

Similarly, there were two different types of vertical formwork observed on the third project: rented Aluma System forms and handset forms. Handset forms were used on this project as foundation forms, as well as bulkheads on wall forms. The mapped workflow for this project shows the formwork use cycle for the handset wooden bulkhead forms. The first use cycle of the bulkheads is the stockpile-prepare-move-assemble-erect-pour-cure-strip-move-clean-move-stockpile sequence represented in Figure 5. The second and last use cycle for the bulkheads begin after the stockpile step in the previous cycle and follow the sequence of move-erect-pour-cure-strip, ending with the decision to re-use or not. Based on conversations with the workers and management of the construction firm, this decision is based on visual inspection and a rough estimate in the field of the costs associated with transporting and temporarily storing the formwork before use on another project.

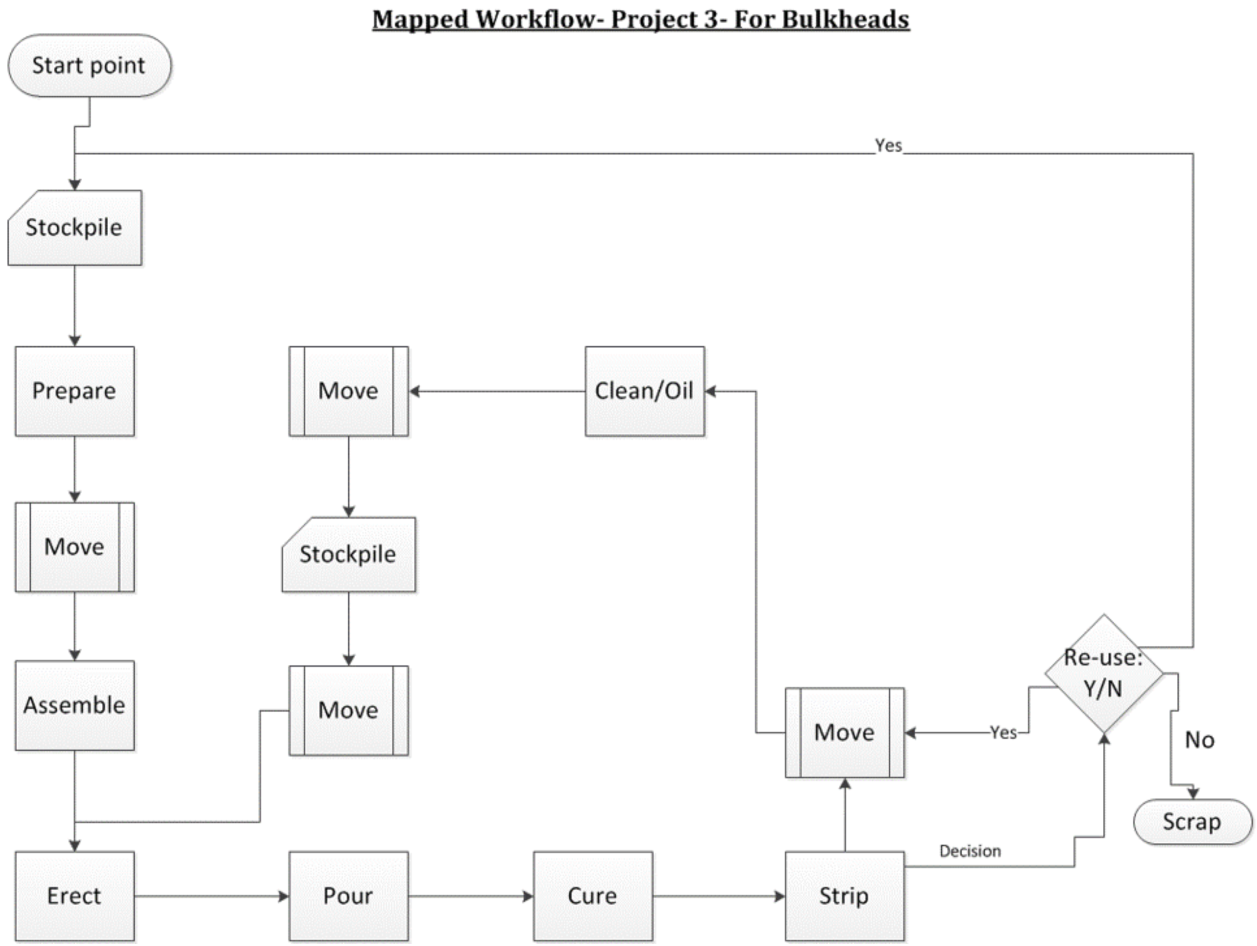

Figure 5: Mapped Workflows in Project 3

The general model presented above was validated in the research. The particular workflow model on each project was obtained by setting project-specific activities that were non-existent to have zero duration. Based on this approach the general model was used to represent all three projects. The use of the general model to describe formwork activities should be further validated against additional construction projects.

3. OSHA Case Study Results

A detailed statistical summary of the categorization of the 438 incidents associated with concrete formwork that were found in the OSHA Fatality and Catastrophe Incident Summaries is shown in Table 2. The OSHA summaries typically do not report low severity incidents. Low severity incidents were defined as those incidents that lead to temporary discomfort/pain or minor first aid required with limited impact on work time. Furthermore, the OSHA summaries do not typically describe near miss incidents. This drawback in the incident data limits the ability for the data to accurately reflect the true distribution of injury severities related to formwork throughout the construction industry.

Out of the 438 incidents, 2 incidents were classified as Near Misses (disruptive incidents that resulted in no injury, but had a significant impact on the project), 20 were of Low Severity (temporary discomfort/pain or minor first aid required with limited impact on work time, but had significant impact on the project), 203 incidents of Medium Severity (major first aid required or medical case, along with lost work time greater than a day), and 213 incidents of High Severity (incidents leading to permanent disability or fatality). A total of 177 of the 213 High Severity incidents were fatalities. It is to be noted that in Table 2, 'total' refers to the total number of incidents related to each activity, while 'Net total' refers to the total number of incidents recorded which are related to formwork use (438). The distribution of injuries for each activity in the formwork cycle is shown in Figure 6.

Table 2: OSHA Formwork Incident Summaries: According to Severity and Activity

Activity		Assembly	Erection	Forming	Transportation	Pouring Concrete	Stripping	Other	Not Specified
Near Miss	**No. of incidents**	0	0	0	0	1	0	0	1
	% of total*	0.00%	0.00%	0.00%	0.00%	0.89%	0.00%	0.00%	5.00%
Low Severity	**No. of incidents**	1	4	1	1	6	3	3	1
	% of total*	5.00%	4.12%	2.38%	7.14%	5.36%	3.41%	6.67%	5.00%
Medium Severity	**No. of incidents**	9	49	13	4	62	41	18	7
	% of total*	45.00%	50.52%	30.95%	28.57%	55.36%	46.59%	40.00%	35.00%
High Severity	**No. of incidents**	10	44	28	9	43	44	24	11
	% of total*	50.00%	45.36%	66.67%	64.29%	38.39%	50.00%	53.33%	55.00%
Total Number of incidents / activity	**No. of incidents**	20	97	42	14	112	88	45	20
	% of Net total**	4.57%	22.15%	9.59%	3.20%	25.57%	20.09%	10.27%	4.57%

Legend:
* 'total' refers to the total number of incidents related to each activity
** 'Net total' refers to the total number (438) of incidents recorded, which are related to formwork use

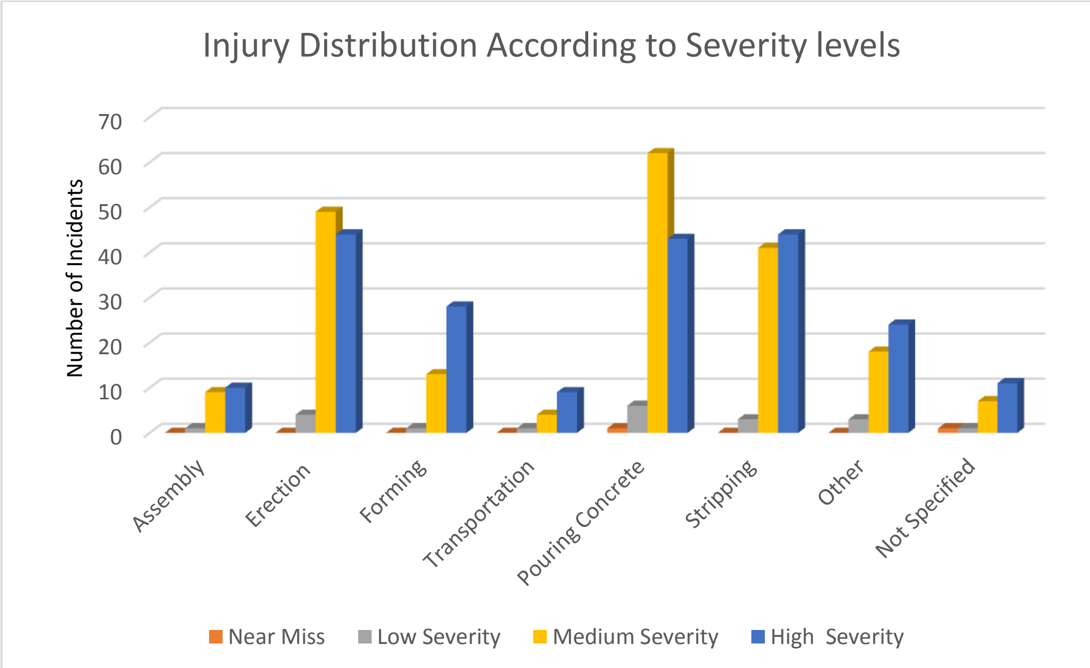

Figure 6: Number of Incidents categorized by Activities

Table 3 and Figure 7 show the number of fatalities associated with each activity and according to severity level. The largest number of fatalities (40 fatalities, 93.02% of High Severity incidents) is associated with the activity of Pouring Concrete. It is worth noting that although it is not possible to distinguish between horizontal formwork and vertical formwork in many OSHA cases reviewed, most incidents of high severity that related to Pouring Concrete occurred during the use of horizontal formwork.

The number of fatalities was also classified according to the activity being performed at the time of occurrence of the incident. The percentage of fatalities relative to the number of just High Severity incidents, as well as to the number of total incidents in each category can be found in Table 3. As seen in Figure 8, the activity with the largest number of fatalities occurred within Pouring Concrete (40 fatalities) followed by Stripping (38 fatalities). Other activities with a large number of fatalities were Erection of formwork (29 fatalities), and Forming (22 fatalities). The Other category (23 fatalities) specifies incidents in which the worker involved in the incident was performing another activity completely independent of any concrete forming activities. The Not Specified category contains the number of incidents in which it is not possible to determine the ongoing activity due to a lack of detail in the summary.

Table 3: Fatalities associated with each Activity, Relative to High Severity

Activity		Assembly	Erection	Forming	Transportation	Pouring Concrete	Stripping	Other	Not Specified
Total no. of incidents		10	44	28	9	43	44	24	11
Non-fatality	No. of incidents	3	15	6	1	3	6	1	1
Fatality	No. of incidents	7	29	22	8	40	38	23	10
	% of High Severity	70.00%	65.91%	78.57%	88.89%	93.02%	86.36%	95.83 %	90.91%

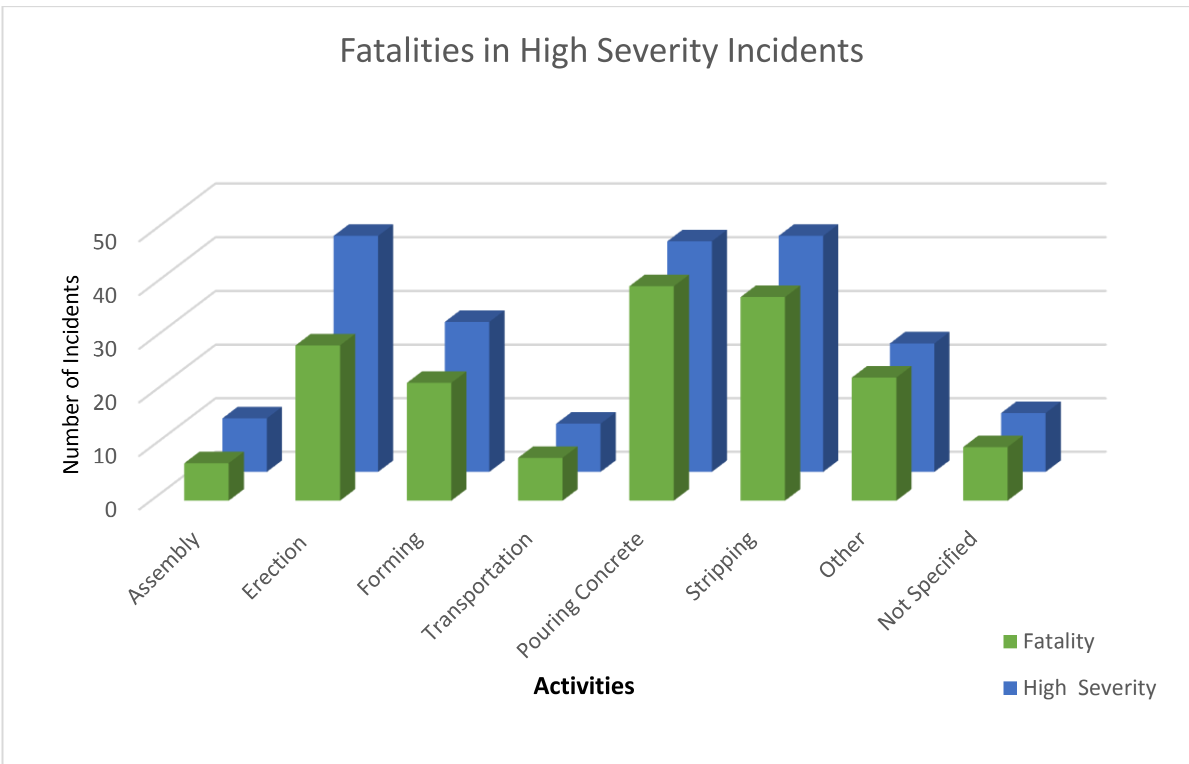

Figure 7: Fatalities Relative to High Severity Incidents

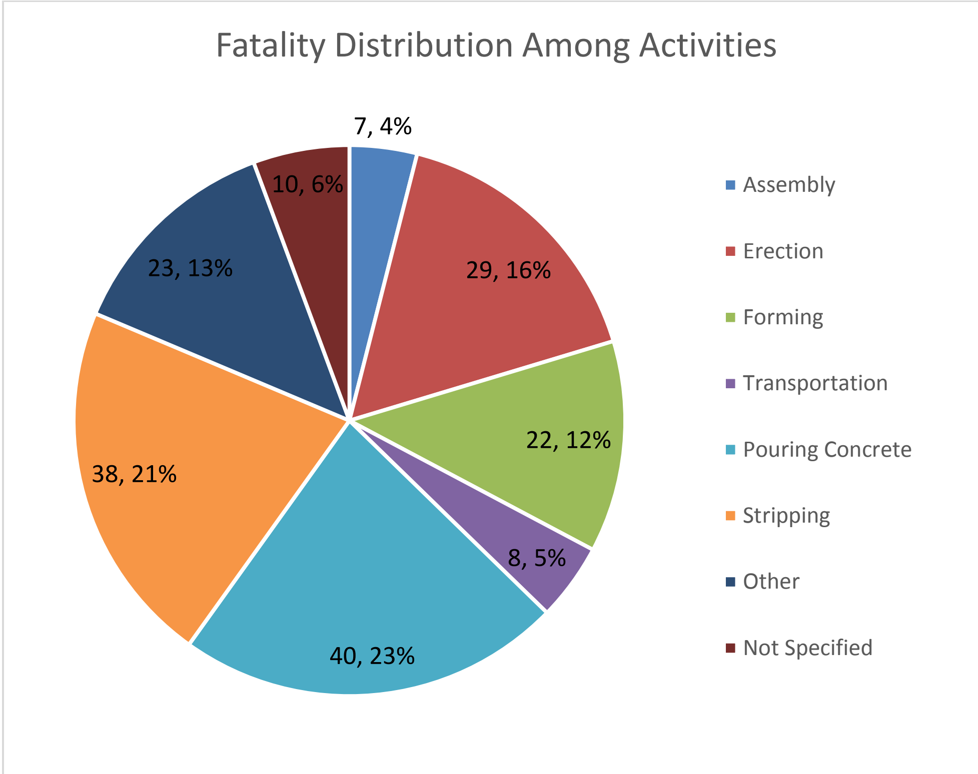

Figure 8: Percentage of Fatalities in each Activity Category

As mentioned above, the lower number of Near Misses and Low Severity injuries could be attributed to the fact that most incidents which meet the definitions for these types of injuries are not injuries that OSHA investigates. OSHA does not typically conduct investigations of near misses and low severity injuries. Injuries of this severity are not investigated unless they occur as part of an incident that includes a higher severity injury.

Since OSHA Fatality and Catastrophe summaries do not provide in-depth detail of every incident, in many cases, it is not possible to determine the exact conditions and type of formwork being worked on at the time of incident (i.e., horizontal formwork or vertical formwork), the safety culture on the project, surrounding hazards, and the specific activity performed by the worker involved in the incident. Most importantly, the root cause of the incident itself is not described in detail. For some incidents, the case summaries do not give a clear idea of the incident scenario, which could lead to the incident being assigned to a different severity level. It is worth noting that for some incidents there was just sufficient information available to understand that the employee was engaged in preparation, assembly, or erection of formwork during the occurrence of the incident, but not enough to assign the incident specifically to any of the mentioned activity categories. For such cases, the activities were assigned to the activity of Forming, which comprises both Assembly and Erection activities.

4. Laboratory Testing Results

Laboratory testing was carried out to measure any possible deterioration in shear and bending capacity of the plywood sheathing used in formwork as the number of uses increases. Please refer to the ASTM standards for a description of the testing methodologies and assumptions associated with each standard test described below.

THIRD POINT BENDING

Plywood specimens of 0 uses, 2 uses, 5 uses, 8 uses, 11 uses, and 14 uses were tested from Project 1, and the maximum load and the induced bending stress values were obtained. The test statistics of average maximum load and average maximum bending moment per use, for all specimens prepared from Project 1 samples can be seen in Table 4, corresponding to Figure 9 and Figure 10, respectively. The number of samples tested was ten (n = 10) for each number of use cases and for each of the third-point and five-point bending tests.

Table 4: Test Statistics for Third Point Bending Tests, Project 1

# of Uses	Mean Max Load	Std Dev. Max Load	Mean Bending Moment	Std Dev. Bending Moment	COV[1]
	(lbf)	(lbf)	(lbf-in)	(lbf-in)	%
0	513.8	85.48	2226.55	370.41	17.01
2	501.3	106.69	2172.18	462.31	21.76
5	743.8	107.94	3223.21	467.73	14.84
8	484.0	148.52	2097.33	643.61	31.38
11	593.9	88.13	2573.61	381.90	15.17
14	605.7	80.25	2624.82	347.76	13.55

[1]COV – coefficient of variation

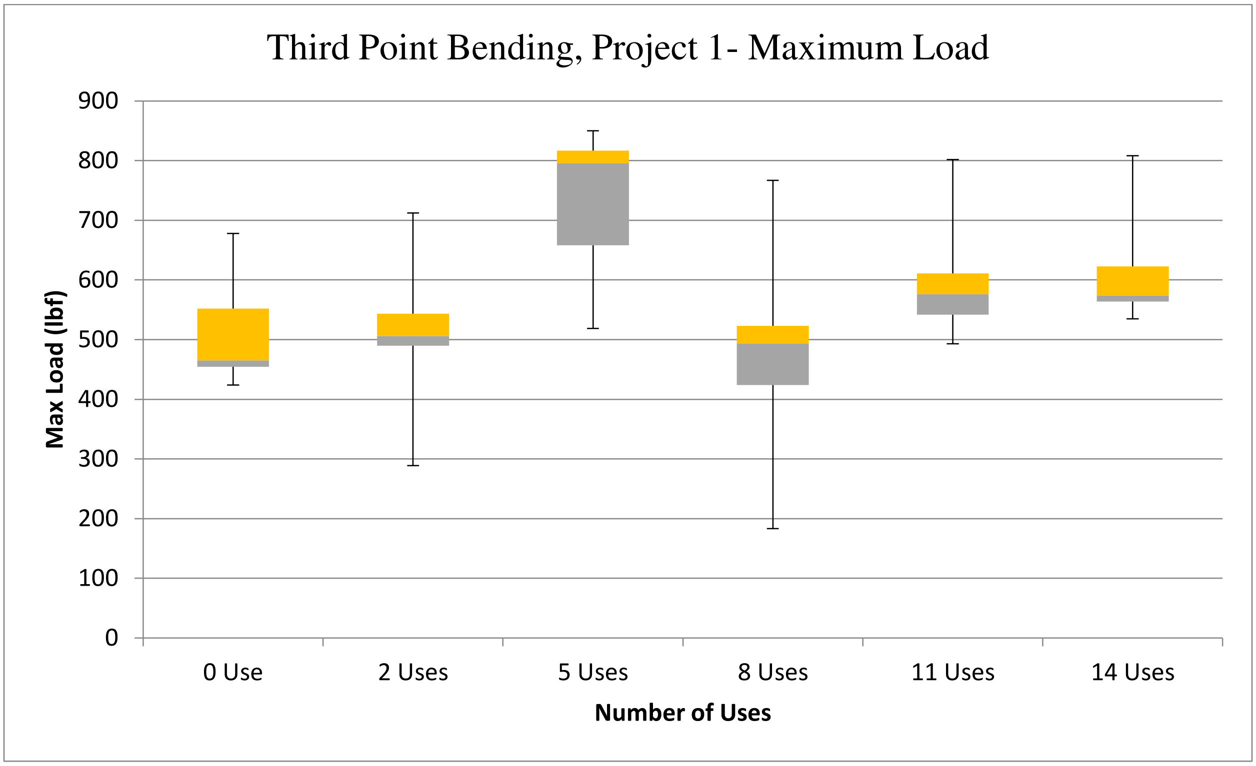

Figure 9: Box Plot, Maximum Load from Bending Tests, Project 1

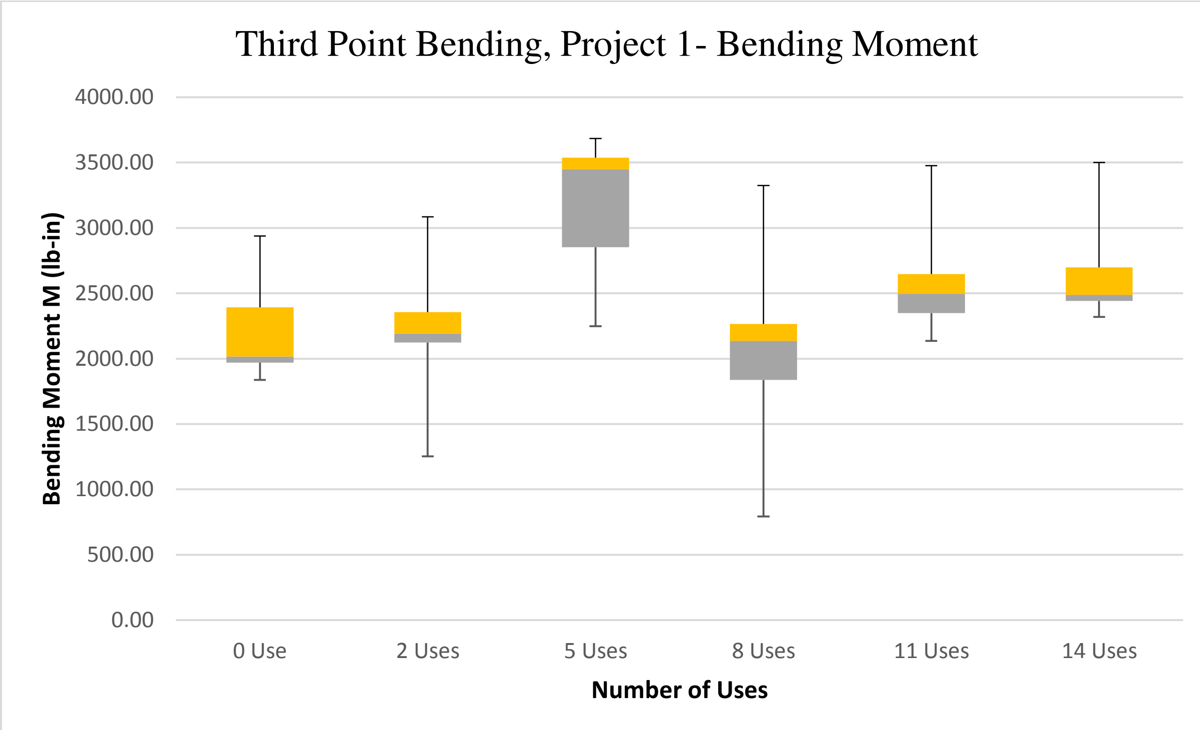

Figure 10: Box Plot, Calculated Bending Moment from Bending Tests, Project 1

It can be seen that the average maximum load decreases from 0 uses to 2 uses, increases to the highest value at 5 uses, and comes down to the lowest value at 8 uses. The average maximum loads for 11 uses and 14 uses are similar, falling lower than the value for 5 uses, yet above the average maximum load value for 0 uses. The test statistics for average bending moment per use follow the same trend as the average maximum load: the highest average bending moment value corresponded to 5 uses, followed by 14 uses, 11 uses, 0 uses, 2 uses, and 8 uses at the lowest. The median value trend is the same as the mean value trend in both cases. Analysis and discussion to understand these results are provided below.

The test statistics for the average maximum load per use and the calculated bending moment per use for specimens prepared from Project 3, using third point bending tests are shown in Table 5. Project 3 was a small project and only formwork with up to two re-uses was available for testing. The corresponding box plots can be seen in Figure 11 and Figure 12, respectively. The test statistics for maximum load show that specimens with 0 uses had the highest average capacity, followed by samples with 2 uses, and finally with 1 use. However, the median maximum load shows a slightly different trend, with 0 uses being the highest, followed by 1 use, and then 2 uses.

Table 5: Test Statistics for Third Point Bending Tests, Project 3

# of Uses	Mean Max Load/Use	Std Dev. Max Load/Use	Mean Moment/use	Std Dev. Moment/Use	COV[1]
	(lbf)	(lbf)	(lbf-in)	(lbf-in)	%
0	443.00	96.37	1605.88	349.34	22.21
1	337.50	91.62	1223.44	332.11	27.71
2	347.71	135.09	1260.46	489.69	39.66

[1]COV – coefficient of variation

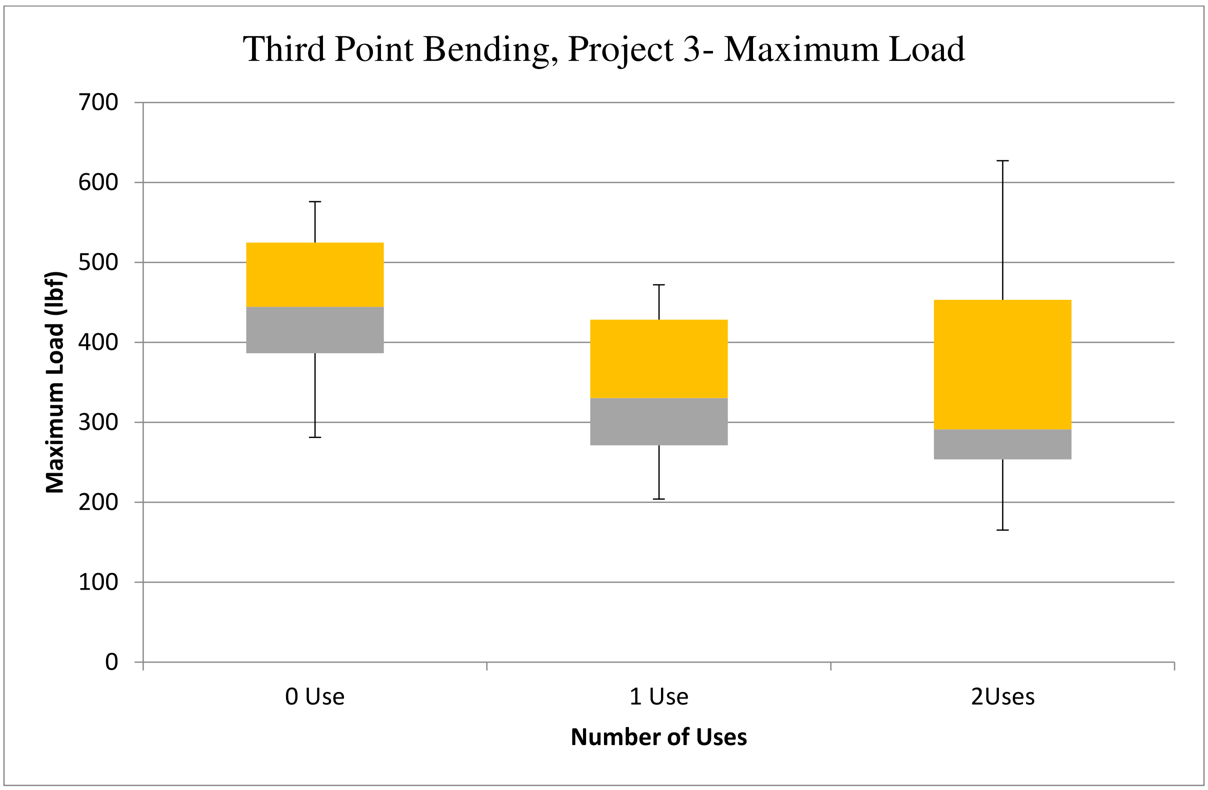

Figure 11: Box Plot, Maximum Load from Bending Tests, Project 3

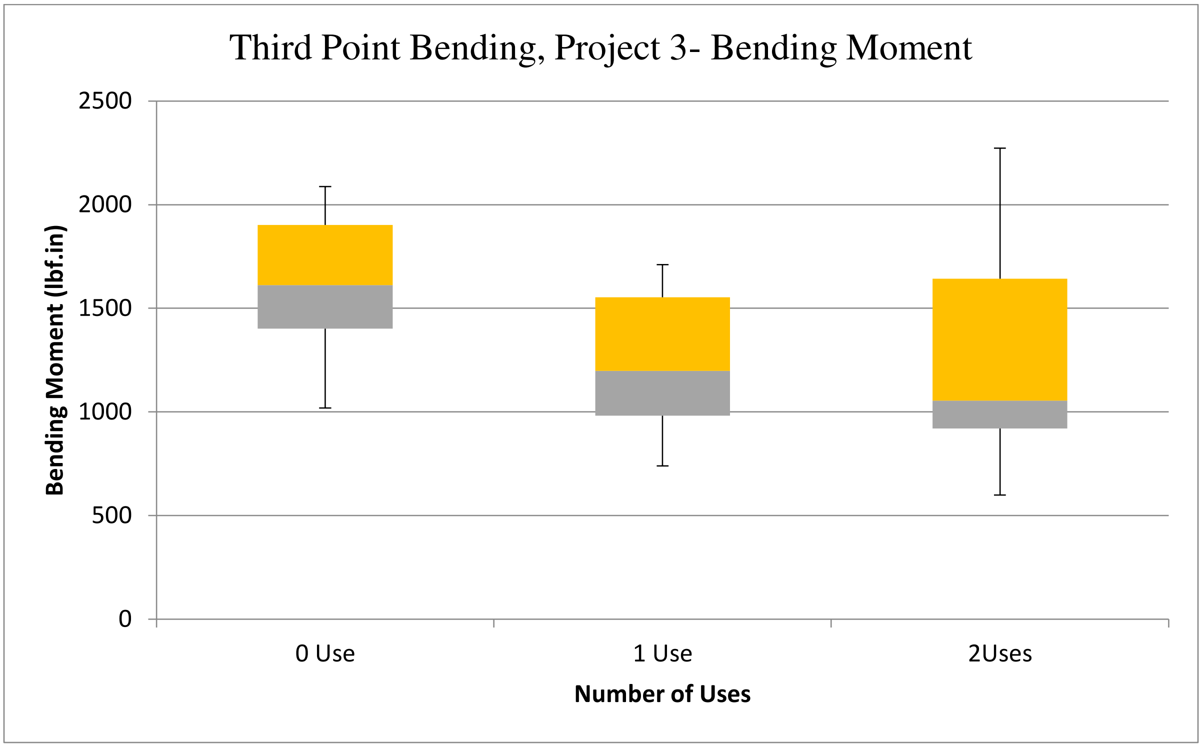

Figure 12: Box Plot, Calculated Bending Moment from Bending Tests, Project 3

The test statistics for the average bending moment per use for specimens prepared from Project 3, calculated using the maximum loads obtained can be viewed in Table 5 and Figure 12. The test statistics for bending moment exhibit the same trend, in descending order – 0 uses, 2 uses, and 1 use – and the value of the median bending moment is 0 uses being the highest, followed by 1 use, and then 2 uses.

FIVE POINT BENDING (SHEAR)

The test statistics for the average maximum load per use and the induced shear stress per use for specimens prepared from Project 1, tested using five point bending shear tests, can be viewed in Table 6, and the corresponding box plots can be seen in Figure 13 and Figure 14. The test statistics for maximum load show that specimens with 8 uses had the highest average capacity, followed by samples with 5 uses, 0 uses, 2 uses, 11 uses, and finally with 14 uses, in descending order. The median values also show the same trend.

The test statistics for average induced shear stress show that specimens with 8 uses had the highest average capacity, followed by samples with 5 uses, 0 uses, 2 uses, 14 uses, and finally with 11 uses, in the mentioned order. The median values follow a different order – 5 uses, 8 uses, 0 uses, 2 uses, 11 uses, and 14 uses – in descending order of magnitude.

Table 6: Test Statistics for Five Point Bending Tests, Project 1

# of Uses	Mean Max Load/Use	Std Dev. Max Load/Use	COV[1]	Mean Induced Shear Stress/ Use	Std Dev. Induced Shear Stress/Use	COV[1]
	(lbf)	(lbf)	%	(psi)	(psi)	%
0	3517.88	169.06	4.91	533.03	27.97	5.38
2	3266.78	230.39	7.21	487.94	30.56	6.42
5	3539.76	234.60	6.78	551.13	39.16	7.28
8	3608.45	319.11	9.04	554.16	51.83	9.59
11	3035.26	298.89	10.07	443.24	37.85	8.75
14	3025.93	157.74	5.33	463.07	33.46	7.41

[1]COV – coefficient of variation

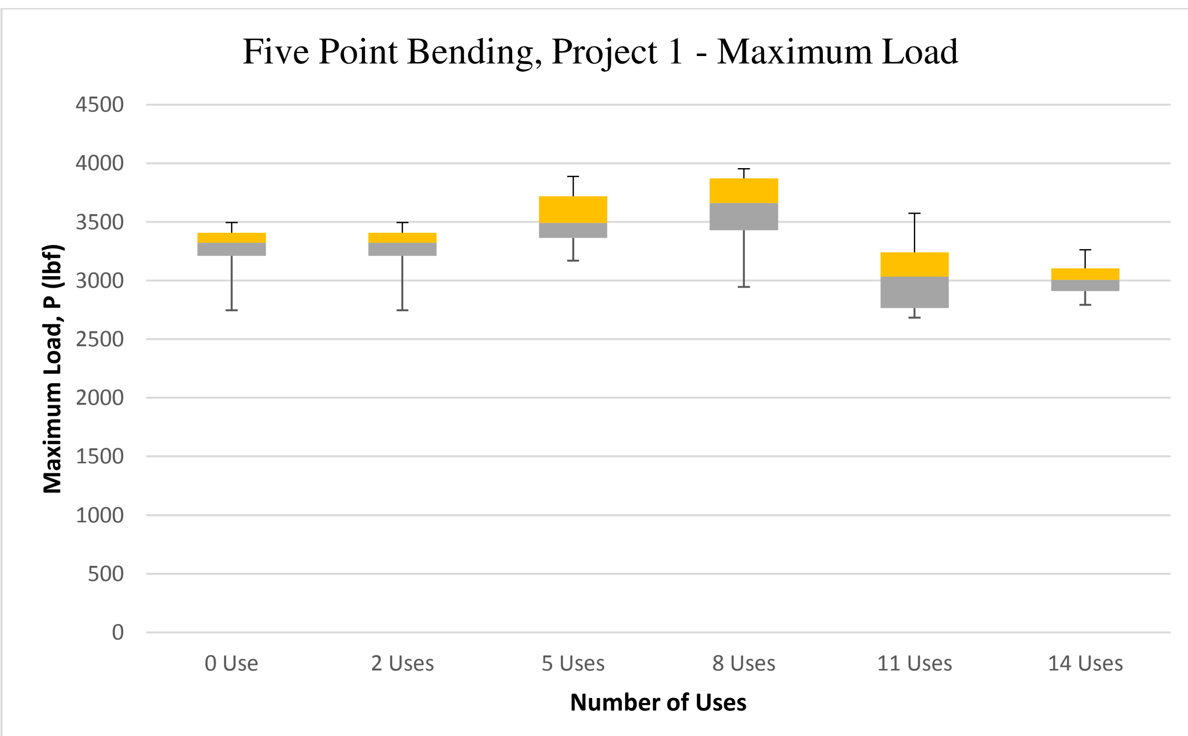

Figure 13: Box Plot, Maximum Load from Rolling Shear Tests, Project 1

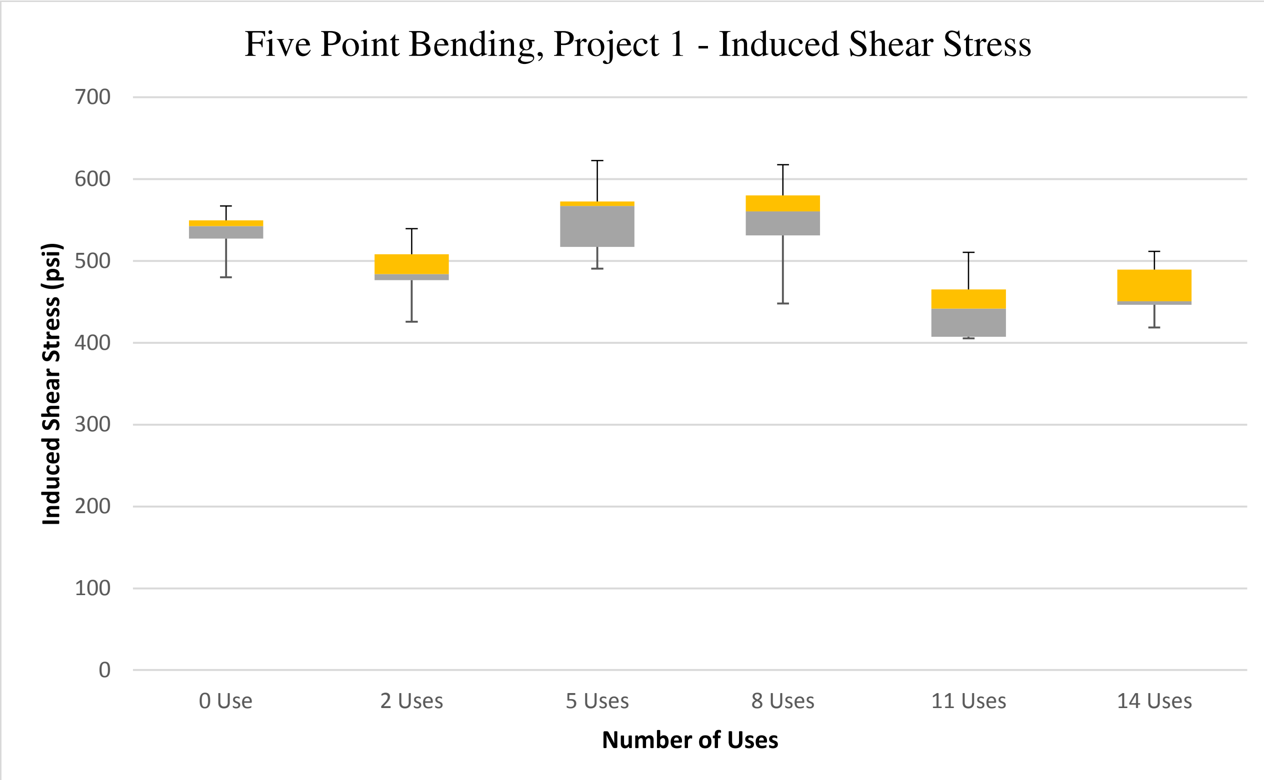

Figure 14: Box Plot, Induced Shear Stress from Rolling Shear Tests, Project 1

The mean maximum load per use and induced shear stress per use for specimens prepared from Project 3 samples, obtained from five point bending tests, have the test characteristics shown in Table 7. The corresponding boxplots can be found in Figure 15 and Figure 16, respectively. The magnitude of the test value for the average maximum load per use, in descending order, is: 1 use, 2 uses, and 0 uses. The median values also exhibit the same trend.

Table 7: Test Statistics for Five Point Bending Tests, Project 3

# of Uses	Average Max Load/Use	Std Dev. Max Load/Use	COV[1]	Average Induced Shear Stress	Std Dev. Induced Shear Stress	COV[1]
	(psi)	(psi)	%	(psi)	(psi)	%
0	1628.37	148.93	9.34	399.85	191.85	48.98
1	1891.56	63.02	3.40	468.87	219.90	47.88
2	1675.36	146.24	8.91	405.15	191.63	48.28

[1]COV – coefficient of variation

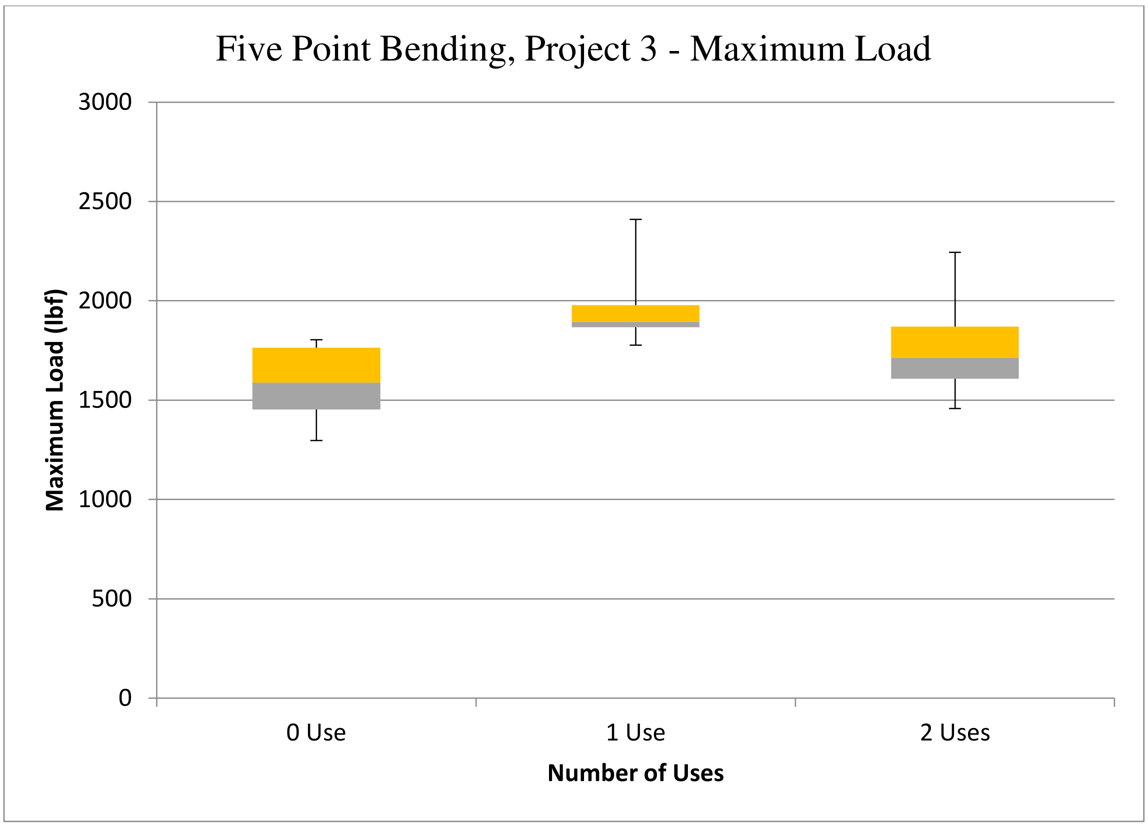

Figure 15: Box Plot, Maximum Load from Rolling Shear Tests, Project 3

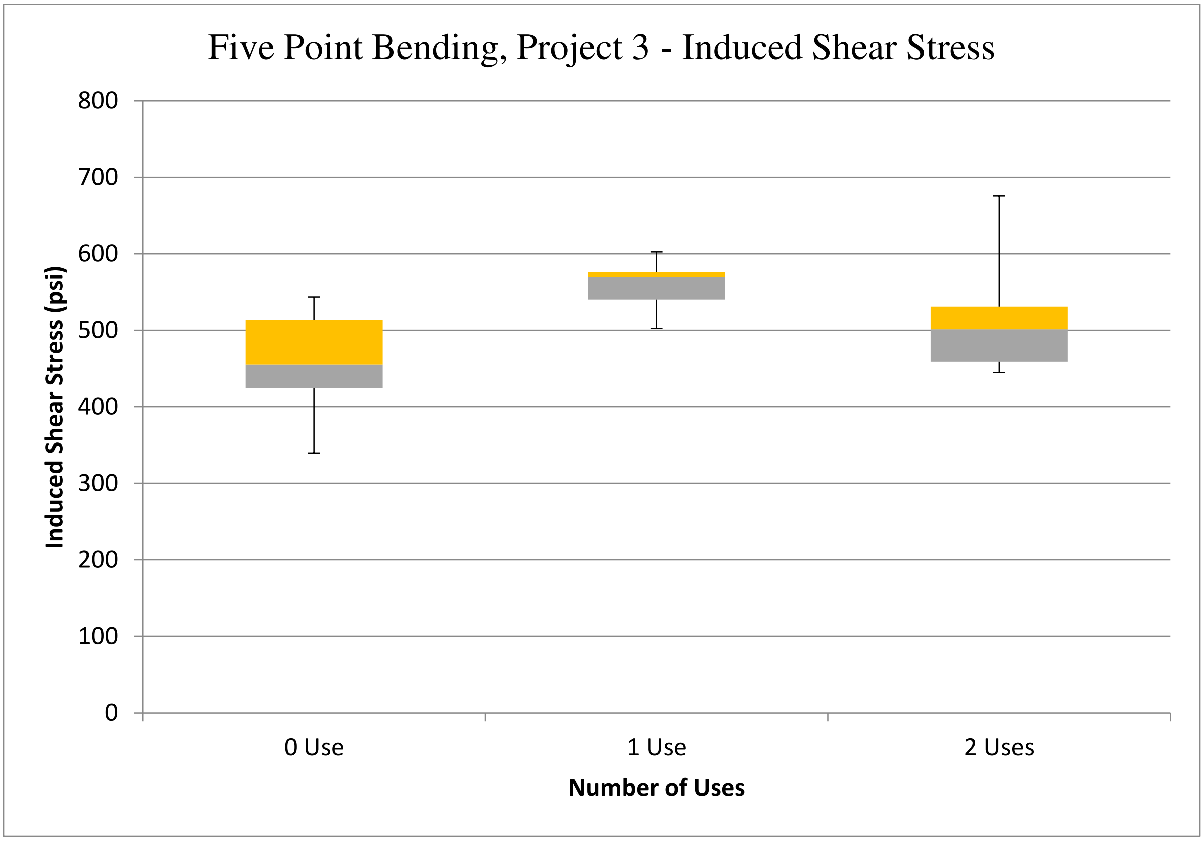

Figure 16: Box Plot, Induced Shear Stress from Rolling Shear Tests, Project 3

For the average induced shear stress per use for specimens prepared from Project 3, the trend of mean and median values exhibited is the same as the trend exhibited by the average maximum load for Project 3 specimens obtained by five point bending tests – 1 use, 2 uses and 0 uses – in the decreasing order of magnitude.

It can be seen from the above results that the testing results exhibit a mixed trend. The expected trend was that the sample specimens with lower number of uses would exhibit higher capacity, with specimens of 0 uses having the maximum value. However, this was not observed in the testing. The possible reasons for this are discussed later in this section.

It was found that keeping track of the number of uses is not something usually done in the industry. In the cases where sheets of plywood were used for the first time on any of the three projects, it was possible for the research team to track the number of uses that the plywood was subjected to. The primary reason for not conducting any testing on the sample panels obtained from Project 2 was that, apart from the new sheets of plywood, there were no means available to identify with any certainty the number of uses that the used plywood panels had been subjected to. The inability to track the number of uses on this project was due to a variety of reasons related to the construction process and work flow, including the fact that the formwork was handset as opposed to pre-assembled panels.

Samples were collected from both projects as panels of varying sizes. However, there was often only one panel with a certain confirmed number of uses available. The variation of properties in plywood can be large, as can be seen from the large coefficients of variation obtained by testing specimens prepared from one or two panels. In addition, additional unaccounted variation could be introduced into the test data as the samples of different uses obtained could have come from different sources. That is, the samples may be made with different types of wood or glue, or manufactured in a different way and at a different facility. It is assumed that the sample panels at least come from the same manufacturer, as companies use the same supplier for plywood through extended periods of time. Even then, it may not be the case that all samples belong to the same batch. Performing the research in a laboratory where the exact number of uses and material selection can be controlled would help alleviate this problem. If controlled testing in a laboratory setting is performed, and thus addressing the main variables that influence strength degradation, the research can enable setting a safe number of re-uses as a function of those variables. Laboratory testing would additionally enable comparison of multiple batches with zero uses in order to obtain baseline material properties.

In this study, significant variations were observed in the dimensions of the specimens prepared from the obtained samples and in thickness of the sample specimens. These variations were accounted for by measuring the thickness and width of each specimen at four different points on the specimen and then using an average value thus obtained for subsequent calculations. All of the tests were set up and carried out by the same operator in an effort to minimize variations in the testing method and the test setup.

Additionally, from the formwork monitoring, it was observed that some formwork panels had different exposure patterns depending on the concrete pour schedule and the weather conditions. The pour schedule dictates the length of time the formwork is exposed to the weather and to other impacts related to ongoing construction operations. Some forms were exposed to rain and to additional stresses during storage, such as workers climbing on them. Furthermore, some formwork panels were subjected to alternate use before being re-used (e.g., formwork panel being used as a work platform). Variations due to these exposures are not accounted for in the testing. Panel wear and any observable damage was noted for each sample.

5. Risk Assessment Results using Safety Survey and Risk Model

A total of 32 complete responses (n = 32) were obtained from respondents who actively handle formwork as a part of their daily job. As seen in the mapped workflow for general formwork use, there are 18 steps, out which 13 activities were deemed to pose some amount of risk to the workers involved. Each row in the survey template corresponds to an activity, in sequential order. All columns were filled in by the workers. The first column to be filled in asks the respondents to enter the percentage of time spent working on each activity. The second column requires the frequency of near miss incidents, rated according to the numerical frequency scale (ranging from 0 to 10) provided in the methodology overview. Similarly, the third, fourth, and fifth columns ask the respondent to fill in the frequency of low, medium, and high severity incidents corresponding to the activities in each row. A portion of the safety survey table with sample responses can be seen in Table 8. It is important to note that the survey did not address the types of failures that lead to the injuries. The participants were asked to focus on the injury severity regardless of the nature of the incident or whether the formwork failed or not.

Table 8: Sample Safety Survey Response (Partial)

ACT. NO.	ACTIVITY EXPOSURE* (%)	ACTIVITY	ACTIVITY DESCRIPTION	POSSIBLE FREQUENCY OF INJURY (Frequency of injury on a scale of 0 – 10)			
				Near Miss	Low Severity	Medium Severity	High Severity
1	20	Moving	Unloading and carrying plywood/wood/other form components from trucks to stockpile on site	7	5	4	2
2	40	Preparation	Cutting plywood/2x's into the necessary sizes and shapes required to construct a formwork panel using a handsaw, saw horses, etc.	9	7	5	3

*The percentage of time that the worker conducts the activity out of the total time for the formwork cycle. Some activities may overlap; therefore the total sum of exposures may not add up to a 100%.

Average frequency values for each activity and for each severity level were calculated, and the average exposure of respondents to the risk associated with each activity was calculated. The mean responses obtained for each of the five input columns are displayed in Table 9. It can be seen that the largest value for exposure is 40%, for Assembling Forms (Activity No. 4), meaning the respondents, as an average, perceive that the longest duration of exposure to any existing risk occurs during the activity of assembling forms. The highest average frequency value is 6, corresponding to an incident every six months, for near miss incidents during the activity of Moving. The average is calculated here rather than the median or mode, as the available responses are further used as inputs into the risk simulation software @Risk, to obtain the total unit risk and the total cumulative risk, as well as to identify the activities that affect the total risk values the most.

Table 9: Average Values of Responses Obtained

Act. No.	Activity	AVERAGE RESPONSE VALUES (n = 32 respondents)				
		Activity Exposure	Near Miss (Severity/ incident)	Low Severity (Severity/ incident)	Medium Severity (Severity/ incident)	High Severity (Severity/ incident)
1	Stockpile	15.56	5.33	4.89	3.22	1.78
2	Preparation	37.78	5.00	5.11	3.56	2.11
3	Moving (Optional)	32.22	6.00	5.67	3.44	2.00
4	Assembling Forms	40.00	5.56	5.00	3.33	2.22
5	Stacking Prepared Forms	17.78	5.22	5.00	3.33	1.67
6	Moving	15.56	5.11	5.00	3.67	2.22
7	Erection/Placing Forms	34.44	5.67	5.00	3.56	2.56
8	Pouring Concrete/Curing	20.56	4.67	4.33	3.00	2.33
9	Stripping Forms	25.56	5.67	5.33	3.33	2.00
10	Move forms	16.67	5.44	4.67	3.33	1.56
11	Dismantling/ Cleaning Forms	15.56	4.78	4.11	2.78	1.11
12	Move forms/ Form Components	20.00	4.89	4.33	3.00	1.44
13	Stack/ Stockpile Forms	17.22	5.11	4.56	3.44	1.56

The final section of the safety survey posed an open-ended question to the respondents regarding the factors that increase or decrease the risk of injury while working with formwork. The most frequent responses obtained were tabulated and can be seen in Table 10.

Table 10: Factors that Affect Risk of Injury

Factors that increase the risk of injury	**Factors that decrease the risk of injury**
Weather conditions	Pre-task planning
Tight schedule	Collect tools and supplies
Drug/alcohol abuse	Effective communication
Lack of proper tools/equipment	Good morale
Lack of sleep	Proper access and use of proper safety gear
Lack of experience, training	Sufficient sleep
Lack of communication	Team work
Lifting too much weight	Clean/tidy site

6. Reliability Assessment

The reliability indices, and the probabilities of failure calculated from them, are discussed in this section. Table 11 shows the values of β for bending (β_1) and for shear (β_2). The test data obtained had a few outliers, which were much higher or lower than the average values. To assess if the removal of outliers had any effect on the reliability indices, the indices were calculated with the outliers removed from the data set also (β_1' and β_2' in the table). The corresponding probability of failure (P_f) can also be found in the table in the columns adjacent to each column of β_1, β_2, and β_1'and β_2'. From these calculations, all samples from Project 1 and Project 3 show low to moderate probabilities of failure. The degree of uncertainty due to the large range exhibited in the testing results also has an effect on the β and the P_f values. As noted above, ten samples were tested for each number of uses.

Table 11: β and P_f for All Tested Samples, With and Without Extreme Outliers in the Test Data

	No. of Uses[1]	Bending, with outliers		Bending, without outliers		Shear, with outliers		Shear, without outliers	
		β_1	P_f	β_1'	P_f	β_2	P_f	β_2'	P_f
Project 3 Samples	0 uses	3.11	0.1%	2.42	0.8%	3.82	0 %	5.74	0 %
	1 use	2.27	1.2%	0.96	16.9%	13.14	0 %	14.95	0 %
	2 uses	1.60	5.5%	0.46	32.3%	4.53	0 %	8.30	0 %
Project 1 Samples	0 uses	1.73	4.2%	0.59	27.8%	13.34	0 %	16.68	0 %
	2 uses	1.19	11.8%	0.38	35.1%	10.87	0 %	14.60	0 %
	5 uses	3.63	0 %	1.29	9.8%	10.18	0 %	11.56	0 %
	8 uses	0.85	19.9%	0.58	28.2%	7.82	0 %	10.83	0 %
	11 uses	1.82	3.5%	0.65	25.7%	7.74	0 %	7.89	0 %
	14 uses	2.34	1.0%	0.81	20.9%	9.27	0 %	10.00	0 %

[1] n = 10 samples for each number of uses

The P_f values shown in Table 11 for both shear and bending capacities are consistent with the onsite observations as no formwork failure was observed at either project. The high probabilities of failure values observed in some cases could be attributed to the conservative estimate of design load demand obtained. Hence, reliability indices were calculated for Project 1 and Project 3 with three levels of uncertainty: COV = 10%, 30%, and 50%. The COV values are obtained following general uncertainty design tables proposed in the *FEMA P695: Quantification of Building Seismic Performance Factors* (ATC, 2009) document. The values calculated can be seen in Table 12 and Table 13 for Project 3 and Project 1, respectively. It is worth noting that no additional bias was considered.

Table 12: β and P_f for Project 3 Samples, With Assumed Standard Deviation for Demand

	No. of Uses[1]	Bending, with outliers		Bending, without outliers		Shear, with outliers		Shear, without outliers	
		β_1	P_f	β_1'	P_f	β_2	P_f	β_2'	P_f
	COV = 10%								
Project 3 Samples	0 uses	2.91	0.2%	2.01	2.2%	4.52	0 %	6.66	0 %
	1 use	1.48	6.9%	1.06	14.5%	14.29	0 %	16.05	0 %
	2 uses	0.88	19.0%	0.76	22.4%	5.21	0 %	9.45	0 %
	COV = 30%								
Project 3 Samples	0 uses	2.26	1.2%	1.70	4.5%	3.91	0 %	5.20	0 %
	1 use	1.15	12.5%	0.86	19.4%	8.39	0 %	8.70	0 %
	2 uses	0.74	22.9%	0.68	24.9%	4.52	0 %	6.31	0 %
	COV = 50%								
Project 3 Samples	0 uses	1.69	4.5%	1.35	8.8%	3.18	0.1%	3.89	0 %
	1 use	0.86	19.5%	0.67	25.2%	5.52	0 %	5.60	0 %
	2 uses	0.59	27.7%	0.57	28.4%	3.70	0 %	4.34	0 %

[1] n = 10 samples for each number of uses

There is the possibility of additional variability in the design model for Project 3, as the tested samples were obtained from bulkhead forms, and the design load demand was calculated assuming that loading is similar to that for column forms. It can be seen that as the uncertainty increases, the probabilities of failure (P_f) also increase for β_1, β_2, β_1' and β_2'.

Table 13: β and P_f for Project 1 Samples, With Assumed Standard Deviation for Demand

	No. of Uses[1]	Bending, with outliers		Bending, without outliers		Shear, with outliers		Shear, without outliers	
		β_1	P_f	β_1'	P_f	β_2	P_f	β_2'	P_f
		COV = 10%							
Project 1 Samples	0 uses	1.73	4.2%	1.62	5.2%	12.41	0 %	15.01	0 %
	2 uses	1.16	12.2%	1.14	12.7%	10.22	0 %	13.17	0 %
	5 uses	3.48	0 %	3.51	0 %	9.78	0 %	11.01	0 %
	8 uses	1.25	10.5%	0.83	20.3%	7.64	0 %	10.39	0 %
	11 uses	1.91	2.8%	1.74	4.1%	7.41	0 %	7.56	0 %
	14 uses	2.95	0.2%	2.23	1.3%	8.79	0 %	9.42	0 %
		COV = 30%							
Project 1 Samples	0 uses	1.10	13.5%	1.04	14.9%	7.61	0 %	8.19	0 %
	2 uses	0.77	22.2%	0.83	20.2%	6.54	0 %	7.25	0 %
	5 uses	2.57	0.5%	2.62	0.4%	7.02	0 %	7.50	0 %
	8 uses	0.98	16.3%	0.70	24.2%	6.11	0 %	7.36	0 %
	11 uses	1.22	11.2%	1.24	10.7%	5.24	0 %	5.33	0 %
	14 uses	1.59	5.5%	1.53	6.3%	5.88	0 %	6.11	0 %
		COV = 50%							
Project 1 Samples	0 uses	0.75	22.7%	0.71	24.0%	5.07	0 %	5.28	0 %
	2 uses	0.52	30 %	0.60	27.5%	4.43	0 %	4.69	0 %
	5 uses	1.86	3.1%	1.91	2.8%	5.00	0 %	5.21	0 %
	8 uses	0.74	23.0%	0.55	29.0%	4.65	0 %	5.21	0 %
	11 uses	0.82	20.5%	0.88	18.9%	3.71	0 %	3.76	0 %
	14 uses	1.03	15.3%	1.07	14.2%	4.05	0 %	4.16	0 %

[1] n = 10 samples for each number of uses

• Conclusions and Scope of Further Study

The conclusions drawn from the obtained key findings, and the extent to which the primary objectives set forth have been achieved, are presented and discussed here. A set of recommendations is also provided at the end of this section.

Primary objective #1 was to map the typical use cycle of vertical timber formwork. This was achieved by establishing a sequence of activities that constitute one formwork use cycle, and validated by observing formwork use cycles on three different projects. A clear picture of the different formwork activities being employed on various construction sites was obtained, leading to the development of a mapped workflow of the formwork use cycle. It was found that the general site lifecycle of vertical concrete formwork incorporates up to 18 steps that include a combination of: moving, stockpiling, and preparing materials; assembling and erecting formwork panels; panel loading (concrete pour); formwork stripping; visual inspection; cleaning; and dismantling/re-using. When the formwork materials can no longer be used due to their physical condition, the workflow model ends with moving the materials to scrap or putting them to use in other ways. The workflow, however, is not consistent from project-to-project. Some of the steps may not take place on a project. The general mapped workflow can be applied to any project by adjusting the workflow, if needed, to eliminate the unnecessary steps. This can help in identifying and keeping track of the number of uses, as well as monitoring the degradation of the formwork. It can also be used as a value stream map for identifying improvements in safety and productivity.

Primary objective #2 was to identify the primary factors contributing to risks associated with use and re-use of formwork and evaluate the risks that the workers are exposed to while carrying out various activities in the formwork cycle. The risks posed to the workers were quantified and evaluated using the safety survey, and the results of the survey were used as inputs to a risk model. This resulted in identifying the stripping and erection activities as those activities that have the highest impact on the overall risk associated with formwork use and re-use, taking into account the frequency of injury at different levels as well as the exposure of the worker to the risk. The survey did not explore the types of failures/events that commonly occur in each of the activities; participants were just asked their perspective (frequency and severity) of the injuries that occur as a result of a failure/event. Based on their own perspective of safety risk on the site, in addition to stripping and erection activities, workers identified assembly as an activity that contributes greatly to the cumulative risk in the formwork lifecycle. This result is similar to that found within the OSHA fatality summaries which reveal that concrete pouring, formwork erection, and formwork stripping are the most prevalent activities associated with construction worker fatalities.

Primary objective #3 was to calculate the reliability associated with the use and re-use of formwork, so as to ascertain the ability of the monitored formwork to fulfill its purpose (i.e., support the applied loading without failure). The preliminary reliability calculations reveal that the actual capacity of the concrete form panels (plyform) obtained from testing is comparable to the estimated lateral load demand on the formwork. However, the actual load demand has to be used instead of an estimated load demand for a clearer picture of the formwork's performance and reliability. As a result, the reliability assessment results are mixed due to uncertainties in actual formwork loading on the site and inconsistent design guidance. The uncertainty is mainly due to inherent randomness in the material properties and applied loading of the concrete on the concrete form panels (plyform). High levels of loading on formwork with no resulting failure appear to be related to overly simplified and over-conservative design equations that are currently prescribed in design guides. Further studies are thus needed on the resulting implications on safety.

The ultimate goal of the study was to obtain a mapped formwork use cycle with a measured loss in capacity per use. The loss of capacity per use was then to be linked to an increase in the quantitative risk values – the total unit risk and the total cumulative risk – to the workers handling formwork. Survey participants perceive no degradation in strength with re-use, and their responses provide the safety risk values for each of the different activities in the lifecycle workflow. The reliability assessment relates only to the concrete pour activity and provides an additional factor to the risk quantities at that step. The reduction in capacity per use would also be an indicator of increasing probabilities of failure due to reduction in the mean capacity value and larger uncertainty, i.e., standard deviation, as number of uses increases. Only a moderate degradation was obtained from testing the samples from Project 1 and Project 3, and it was hypothesized that a larger number of uses would be needed in order to see significant/larger degradation in strength. In addition, confounding variables associated with accurately recording the number of re-uses, environmental conditions, and material properties, would need to be addressed in the testing. Thus, the mapped formwork use cycle and the risk model assume no degradation, and therefore no direct impact of the reliability assessment. A degradation trend obtained from further research is needed, which then can be incorporated into both the formwork use cycle as well as to the risk model so as to obtain a formwork model with risk and reliability values that account for degradation.

The mixed trends observed in testing could be attributed to the inherent variability of the material itself. Most test specimens were prepared from just one or two samples per use due to limited availability of samples per number of uses. A true assessment of deterioration in strength due the number of uses requires samples from additional sites, which were not possible as part of this small study. The number of samples selected for testing would need to be large enough to account for confounding factors and enable making conclusions about the impact of deterioration on strength with confidence. Additionally, the estimation of design demand for the formwork may be different from the actual load demand on the formwork, as the value estimated is deemed conservative. Hence, it is suggested that the actual load applied onsite be measured in future work.

This study corresponds to a small CPWR research project, aimed towards providing understanding and quantifying safety risks and the interrelation between risk of formwork with different number of uses and re-uses. The following recommendations for further investigations are proposed based on the conclusions and limitations of this study:

i. Further research should be conducted using a larger sample size in order to quantify the actual deterioration of formwork onsite in addition to loss of capacity by testing, and then factor the results into a similar risk model. This model can emulate a realistic formwork use cycle, where the number of uses is limited, and the risks assigned would increase as the number of uses increase.
ii. Validation of the research study by sampling over a wider population of projects with formwork is needed to increase the applicability of the conclusions of this study to formwork operations in the construction industry as a whole.
iii. The testing of formwork components should be performed using specimens prepared from samples obtained from different panels with the same number of uses, or incorporate samples that have been used in a controlled environment so as to reduce the variability further.
iv. A more accurate estimation of the design demand is needed to make the calculations for the reliability indices and probabilities of failure closer to the true probability values. This can be done by measuring the actual loads on the formwork while it is being used.

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