Activity-Based Safety Risk Quantification for Concrete Formwork Construction

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Abstract: Most of safety risk research focuses on high-severity safety risks for large-scale construction processes. Such studies help firms identify the highest risk processes so they may be targeted for improvement. However, few studies quantify safety risk at the activity level or include low-severity, high-frequency risks that some literatures suggest contribute to a large proportion of total risk. This paper presents research that involved the holistic quantification of risks for the activities associated with the construction of concrete formwork. Three major research efforts are discussed: (1) identification of activities required to construct concrete formwork; (2) selection of an appropriate all-inclusive and mutually exclusive risk classification system; and (3) the quantification of the average frequency and severity levels for each risk classification associated with each activity. To identify formwork construction activities, 256 worker-hours of observation were conducted and the resulting activity descriptions were reviewed and validated by industry professionals. Risk classifications appropriate for this study were created by aggregating relevant literature. Finally, the Delphi method was implemented to individually quantify average frequency and severity using scales that define the entire spectrum of possible values. In total, 130 frequency ratings and 130 severity ratings were obtained over three rounds of Delphi surveys. Results indicate that there are 13 major activities required to construct concrete formwork and the highest risk activities are applying form oil, lifting and lowering form components, and accepting materials from a crane. The data presented in this paper can be used to target specific high-risk formwork construction activities for improvement.

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Introduction

According to the Bureau of Labor Statistics (www.bls.gov), the construction industry, the largest single-service industry in the United States, employs approximately 8% of the American workforce. Data assembled by the Center for Construction Research and Training (2008), however, indicates that construction accounts for approximately 21% of the all occupational deaths from injuries in the United States (1,243) and has the fourth highest fatality rate of all U.S. industries.

Studies in the United Kingdom have shown similar evidence of a disproportionate injury and illness rate. Researchers found that construction workers are five times more likely to be killed and two times more likely to suffer a serious injury than the all-industry average (Carter and Smith 2006). Specifically, the fatality rate in 1998 in the United Kingdom was 5.6 fatalities per 100,000 workers and, during the same year, the average fatality rate in construction for the European Union as a whole was over 13 fatalities per 100,000 workers.

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Many inherent characteristics of the construction industry contribute to the relatively high injury and illness rate including dynamic work environments, industry fragmentation, multiplicity of operations, proximity of multiple crews, and industry culture (Fredericks et al. 2005). Each of these characteristics contributes to unforeseen and unfamiliar hazards or the unsafe behavior of workers. The unsafe work environment in construction has drawn attention from contractors and owners because of the desire to preserve the well-being of the workforce and to avoid Occupational Health and Safety Administration (OSHA) citations. In addition, construction firms are beginning to recognize the connection between safe and healthful construction projects and business performance.

The costs associated with construction injuries and illnesses are staggering. In 2004, the construction industry experienced 460,000 disabling injuries resulting in an estimated cost of $15.64 billion [National Safety Council 2006]. The National Safety Council also reports that there were 1,194 fatalities in 2004, and the average cost of each of these fatalities was approximately $1,150,000. With just under 10.3 million individuals employed in the construction industry in 2004, the average total cost for disabling injuries and deaths can be calculated to be $1,656 per construction employee. Furthermore, the total cost associated with construction accidents accounts for 7.9–15% of the cost of new, nonresidential projects (Everett and Frank 1996) and the average worker's compensation costs are estimated to be about 3.5% of the total project cost (Coble and Hinze 2000).

The figures cited above do not include the high-frequency, low-severity incidents that may serve as a significant proportion of occupational safety and health-related costs. Furthermore, the figures do not account for the indirect costs that may represent

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over half of the total cost of construction accidents (Hinze 1997). Therefore, the true cost of construction safety incidents may be even more compelling.

While the injury and illness rates in the construction industry are high, construction accident rates have declined as a result of the increased pressures from OSHA, increase in contractor awareness, training, and enforcement (Mitropoulos et al. 2005). However, proactive safety and health research is clearly needed. Current methods of safety risk management are informal and subjective. While some contractors use the OHSAS18000 risk database and management information system, this tool does not allow safety managers to identify the safety risk associated with specific work tasks. As a result, most contractors focus their safety efforts using intuition and judgment (Hallowell and Gambatese 2007).

The objective of this paper is to present a method to quantify the comprehensive safety risk at the activity level for a common construction process. Using guidance from literature and the Delphi research method, specific frequency, and severity levels are defined for safety risks associated with the work activities required to construct concrete formwork. While there is an abundance of literature that focuses on quantifying safety risk for large-scale processes (e.g., roofing and steel erection), no studies identified by the writers attempt to quantify the relative safety risk of specific construction work tasks (e.g., lifting materials and ascending ladders). Understanding the relative risk of specific work tasks would allow managers to focus safety program elements such as job hazard analyses and inspections on high-risk activities.

Literature

The structure of the research described in this paper is largely based upon a framework presented in a previous publication by Hallowell and Gambatese (2007) in which the concept of safety risk demand was introduced. Safety risk demand is defined as the total safety risk associated with a construction process. The term demand is analogous to loading on a beam within a structural system. That is, the safety risk demand acts as a "load" on the safety system. This load is resisted by the capacity of the system to support the applied demand. In this analogy, capacity would be represented by the risk mitigated by a safety program. The suggested method for quantifying risk demand for any construction process is illustrated by Fig. 1. In summary, the process involves five steps: (1) identification of applicable safety risks ($R_{1\to N}$); (2) identification of the worker activities required to complete the selected construction process (Act. $A\to Z$); (3) identification and quantification of the probability (p) and severity (s) associated with the risks for each activity; (4) summation of the quantified risks for each activity; and (5) calculation of the total risk demand for the process by summing the total risk values for all activities. Risk demand can be calculated by using

$$\sum_{\text{Act.}=A}^{Z}\left[\sum_{R_1}^{R_n}(\text{Safety Risk})\right]=S_u=\text{Demand} \tag{1}$$

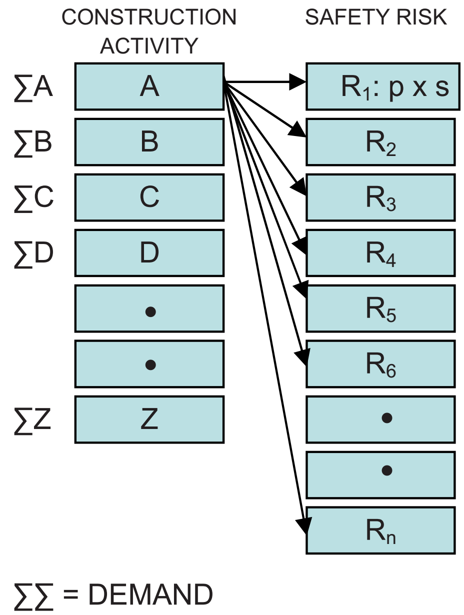

Fig. 1. Safety risk demand

Safety Risks in the Construction Industry

The definition and classification of common construction safety risks is an important step in the process of quantifying safety risk demand. Three main sources of literature define construction safety accident classifications (also referred to as "codes"). The Bureau of Labor Statistics organizes its yearly construction safety data reports in terms of 10 codes while OSHA defines safety risk classifications in terms of 29 primary codes in its Occupational Illness and Injury Classification System. Both OSHA and Bureau of Labor Statistics (BLS) define their injury and illness codes for all industries. Hinze (1997), however, suggests a construction-specific accident classification system that highlights the highest construction-specific safety risks. Using an aggregation of the OSHA, BLS, and Hinze's accident classification systems, the writers selected 10 all-inclusive and mutually exclusive codes for this study. These selected safety risk classifications, with definitions consistent with the literature cited above, are as follows:

1. Struck by;
2. Struck against object;
3. Caught in or compressed;
4. Fall to lower level;
5. Fall on same level;
6. Overexertion;
7. Repetitive motion;
8. Exposure to harmful substances;
9. Transportation accidents; and
10. Other.

Formwork Construction Activities and Risks

The second step in quantifying safety risk demand is to identify the specific activities required to complete a given process. Formwork construction was selected for this study because archival literature, BLS data, and OSHA fatality reports all indicate that formwork construction is associated with a relatively high frequency of disabling injuries and illness. An analysis of 1997 OSHA accident reports revealed that 5.83% of falls were attributed to the construction of formwork or the construction of temporary structures and 21.2% of all struck by accidents involved wood framing or formwork construction (Huang and Hinze 2003). Ergonomic studies also suggest that the repetitive activities of lifting, sawing, and hammering commonly performed by formwork carpenters lead to a high frequency of low-severity injuries

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such as discomfort and persistent pain (Har 2002). Furthermore, formwork construction was selected because it is involved in some capacity on nearly every building construction project and preliminary observations indicated that the work activities required to construct formwork are easily identifiable, encompass the work activities required of many other construction processes, and involve an appropriate number of worker activities for this study.

While much has been written on the topic of formwork safety, no articles were found that specifically identify or describe the worker activities required to complete the process. Therefore, the creation of a comprehensive list of activities became a vital component of this study.

Risk Quantification and Analysis

Over the past decade, several methods of risk quantification have been developed that vary in complexity and application. For example, Everett (1999) analyzed ergonomic risks associated with 65 construction processes (e.g., install drywall and light gauge steel partitioning) using a 1-3 scoring system. Alternatively, Brauer (1994) quantified safety risk by classifying the frequency of event occurrence in subjective levels such as frequent, probable, occasional, remote, and improbable. In a similar approach, Sun et al. (2008) defined risk as the product of frequency and severity and quantified 25 risk factors (e.g., schedule pressure from client) by asking expert participants to rate each component on a subjective Likert scale. Jannadi and Almishari (2003) added the component of exposure to their risk quantification method when developing a risk tool that requires inputs from the user. Finally, Baradan and Usmen (2006) approached safety risk quantification more objectively by quantifying risk for various construction trades using data published by the BLS. As one can see, methods of quantifying construction safety risk and sources of risk data are inconsistent. Not surprisingly, methods of risk analysis vary as well.

When analyzing safety risk data, techniques vary from simple mathematical comparisons of risk ratings to the creation of complex risk tools and techniques. Jannadi and Almishari (2003) used risk scores to populate a risk assessor model with severity, probability, and exposure inputs provided by the user. Alternatively, Sun et al. (2008) used the analytic hierarchy process to assess the status of safety risks on site safety. In an effort to create a risk assessment that is capable of estimating safety risk for common construction practices, Lee and Halpin (2003) created a visual basic program that utilizes fuzzy inputs from the user. Finally, Yi and Langford (2006) developed a methodology for integrating risk assessment with project schedules.

For this research, the writers selected the quantification methods employed by Jannadi and Almishari (2003) and Baradan and Usmen (2006). The equations used to quantify risk are illustrated in Eqs. (2) and (3). According to Eq. (2), unit risk is the product of frequency and severity. As illustrated by Eq. (3), cumulative risk is equal to the product of frequency, severity, and exposure. For both equations, frequency refers to the average number of event per unit of time, severity represents the magnitude of the potential outcome of an event, and exposure describes the duration of contact with a potentially hazardous condition. Frequency is typically expressed in terms of incident rates, severity is defined in terms of impact to the worker or firm, and exposure is defined in units of time

$$\text{Unit Risk} = (\text{Frequency}) \times (\text{Severity}) \tag{2}$$

Table 1. Severity Scale

Subjective severity level	Severity score
Negligible	1
Temporary discomfort	2
Persistent discomfort	4
Temporary pain	8
Persistent pain	16
Minor first aid	32
Major first aid	64
Medical case	128
Lost work time	256
Permanent disablement	1,024
Fatality	26,214

$$\text{Cumulative Risk} = (\text{Frequency}) \times (\text{Severity}) \times (\text{Exposure}) \tag{3}$$

Quantifying the frequency of event occurrence is a seemingly easy task because incident rates are easily measured and tracked. However, obtaining such data can be difficult, especially for risks associated with relatively low severity such as near misses, persistent pain, and first-aid injuries.

While frequency is easily measured, quantifying severity in terms of worker impact is more abstract. Most traditional safety risk analyses utilize data that incorporates only high-severity, low-frequency data tracked by large corporations or the BLS. Such analyses ignore a significant portion of risk. Studies that focus on construction ergonomics have reported that a significant portion of construction related claims involve low-severity incidents. For example, Center for Construction Research and Training (2008) found that strains and sprains accounted for over 37% of all injuries resulting in days away from work. While most of these incidents are not "OSHA recordable" and would not be reflected in BLS annual statistics, they represent a large portion of the yearly workers' compensation costs. If one were to assume that the total number of workers' compensation claims is representative of the cumulative safety risk on a construction site, minor injuries would likely account for a significant portion of the total risk.

To address the limitations of current risk quantification methods, Hallowell and Gambatese (2008) created a set of objective risk scales that incorporate a complete spectrum of frequency and severity levels. The severity scale ranges from negligible injury to fatality and the frequency scale ranges from one incident occurrence every 6 min (0.1 w-h) to one incident occurrence every 100 million or more worker-hours (>100 million w-h). Augmented versions of these scales have been reproduced in Tables 1 and 2. These scales allow one to include all types of incidents in risk analyses given complete incident data and were used to quantify risk for this study.

Typical methods of risk assessment in construction practice involve preconstruction safety meetings, job hazard analyses, and safety inspections during construction. These methods generally focus on risk identification. Evaluating the relative magnitude of risks is generally achieved through intuition, judgment, and word of mouth and risk is mitigated by performing activities such as toolbox talks, orientation and training, and site-specific safety plans (Hallowell and Gambatese 2008). The present study provides an alternative methodology for calculating risk by: (1) objectively quantifying the risks associated with specific activities;

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Table 2. Frequency Scale

Worker-hours per incident	Frequency score
>100 million	1
10–100 million	2
1–10 million	3
100,000–1 million	4
10,000–100,000	5
1,000–10, 000	6
100–1,000	7
10–100	8
1–10	9
0.1–1	10

(2) including high-frequency, low probability risks; and (3) defining risks on well-defined frequency and severity scales that are inclusive and easy to interpret.

This study departs from the existing body of knowledge in several ways. First, it is the only known attempt to conduct an activity-based risk analysis for a specific construction work process. Second, this research involves decomposing risk into specific classifications such as falls to lower level, overexertion, and struck-by. Finally, the frequency and severity scales developed by Hallowell and Gambatese (2008) are used to ensure that all possible outcomes are considered including low-severity injuries that may occur relatively frequently.

Methodology

Two major research efforts were necessary to quantify safety risk demand for formwork construction activities: the identification of required worker activities for the construction of concrete formwork, and the quantification of safety risks associated with each activity. In an effort to create a comprehensive list of worker activities, field observations were conducted and industry surveys were administered. The Delphi method was then employed to quantify the risk levels associated with each activity.

Formwork Construction Activities

Before proceeding with the risk quantification it was necessary to create a comprehensive list of worker activities. As a primer, the research team conducted field observations of crews that were actively constructing concrete formwork. The main objective of the field observations was to create a preliminary list that would later be validated by a group of experienced professionals in an online survey. Field observations were conducted on four projects located in the Pacific Northwest. The projects varied in size from a $100,000 concrete footing to a multistory building project with a budget over $100 million. While all projects involved new construction, the methods of formwork construction varied from site-to-site. One project exclusively used hand-built form components, another used a combination of prefabricated and hand-built components, and the two others exclusively used panelized, prefabricated components.

In total, the research team conducted 256 worker-hours (w-h) of field observations that resulted in recording 12 distinct formwork activities. The observation phase was considered complete when no new activities were observed in 16 continuous worker-hours of observation. Once this requirement was met it was assumed that sufficient repetition had been achieved.

The preliminary list of activities and descriptions was sent to a convenience sample of 12 industry professionals currently employed in the Pacific Northwest. Each of the individuals has over 15 years of industry experience managing and observing the construction of concrete formwork. Respondents were asked to review the list and description of activities and take one of the following actions: (1) confirm that the list is comprehensive and that nothing is incorrect or incomplete; (2) insert additional activities with a brief description; (3) delete inappropriate activities; or (4) revise the activity titles or descriptions as appropriate. In total, all 10 respondents returned a completed survey. Once the activities were defined, the next step was to quantify the average frequency and severity for the risks associated with each activity.

Safety Risk Quantification

To quantify the risks associated with the 13 formwork activities, the Delphi research method was implemented. The objective was to individually quantify the average frequency and severity associated with each safety risk identified in Tables 1 and 2 for each of the 13 formwork construction activities. The sensitivity of this research and the dynamic and transient nature of the construction industry made objective experimental research unrealistic. The Delphi method was chosen because it is particularly useful when objective data are unattainable, there is a lack of empirical evidence, experimental research is unrealistic or unethical, and when the heterogeneity of the participants must be preserved to assure validity of the results. Moreover, the Delphi technique allows researchers to maintain significant control over bias in a well-structured, academically rigorous process using the judgment of qualified experts.

One of the elements that characterize the Delphi method is exclusive use of certified experts. In order to qualify to participate in the study, respondents were asked to complete an introductory survey that solicited information about their backgrounds and experience. Potential expert panelists were identified from current and historic membership lists of nationally recognized safety and health-related committees, such as ASCE's Site Safety Committee, authors of books and journal articles on construction safety and health, and previous Delphi studies on safety. In total, 15 individuals qualified to participate. Expertise requirements were based upon academic and professional experience, committee participation, and professional registration in the engineering and construction industry. Experts were not required to have experience specific with formwork construction.

The specific expertise requirements for this study are based, in part, on the studies of Rajendran (2006) and Rogers and Lopez (2002). Expert panelists were required to meet at least **four** of the following eight characteristics:

1. Primary or secondary author of at least three peer-reviewed journal articles on the topic of construction safety or health.
2. Invited to present at a conference focused on construction safety or health.
3. Member or chair of a construction safety and health-related committee.
4. At least 5 years of professional experience in the construction industry.
5. Faculty member at an accredited institution of higher learning with a research or teaching focus on construction safety and health, or risk management.
6. Author or editor of a book or book chapter on the topic of construction safety and health, or risk management.

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7. Advanced degree in the field of civil engineering, construction engineering, occupational safety and health, or other fields directly related to this study, from an institution of higher learning (minimum of a B.S.)
8. Designation as a professional engineer (P.E.), certified safety professional (C.S.P.), associated risk manager, or a licensed architect (A.I.A.).

The collective qualifications of the selected Delphi panel are as follows:

- Six individuals who possess a Ph.D., six who possess a M.S., and one who possesses a B.S. as their terminal degree in a related field of study.
- Five individuals are employed at the full professor rank and one is employed at the assistant professor rank at accredited academic institutions.
- A total of 186 publications in peer-reviewed journals on the topic of construction safety and health or risk management.
- 29 books on the topic of construction safety and health or risk management.
- 184 years of field experience in the construction industry.
- Six P.E. licenses, one C.S.P. license, and one A.I.A. license.
- Representation of all major geographic regions of the United States.

In addition to the academic rigor, the Delphi method also allows one to design and administer the series of surveys in such a way that simultaneously achieves desired results and minimizes judgment-based biases. A review of social psychology literature revealed eight major biases that may adversely affect the frequency and/or severity ratings provided by the expert panelists. In order to minimize the effects of these biases, several techniques were employed to counteract their effect. First, the list of the 13 formwork construction activities presented on the survey form was randomly ordered for each panelist's custom form using the random number generator in MS Excel. For each panelist the activities were assigned a random number. The random numbers were ranked from highest to lowest and the order of the ranks determined the order to the activities on the survey form. Using a similar methodology, the order of the 10 potential safety risks was randomized for each panelist. Additionally, the median response from the Delphi panel was used to represent the final result, reasons, and median responses from the previous round were included in anonymous feedback to minimize conformity and to identify potentially biased panelists, and independent frequency and probability ratings were solicited to minimize biases that involve neglect of probability. The specific controls and countermeasures for the potential judgment-based biases are included in Table 3.

Participation in the study was strong and consistent. All 15 individuals completed the first round of surveys and 13 of the 15 (87%) completed Round 2 and Round 3. In each round, the panelists were asked to rate the frequency and severity associated with each safety risk for each activity. Panelists were instructed to use the frequency and severity scales shown in Tables 1 and 2. During this process, panelists were provided with anonymous feedback from the previous round. In Round 2, the panelists were provided with the median response from Round 1 and were asked to provide specific reasons for Round 2 responses that were two or more units from the Round 1 median. These reasons and the median values from Round 2 were included as feedback in Round 3. The purpose of the multiple rounds was to achieve a high level of consensus among the expert panelists while the controlled feedback is provided to encourage consensus about the correct value and to avoid conformity. Here, the degree of consensus was measured in terms of absolute deviation (i.e., the standard deviation from the median for each frequency and severity value) and the target value was an average absolute deviation of less than 1 unit on the frequency and severity scales.

Table 3. Controls and Countermeasures for Bias

Bias	Control/countermeasure
Collective unconscious	Include reasons in the controlled feedback to the Delphi panel for each round.
Contrast effect	Randomize the order of questions for each panel member and for each round, and report final results as a median.
Neglect of probability	Require that the probability ratings and severity ratings for each risk are recorded independently.
Von Restroff effect	Include reasons in controlled feedback and conduct multiple rounds of surveys.
Myside bias	Include reasons in the controlled feedback and report final risk ratings as a median.
Recency effect	Identify individuals who have experienced recent events, remove outlying observations, conduct multiple rounds, and report results as a median.
Primacy effect	Randomize the order of questions for each panel member.
Dominance	Ensure anonymity of expert panelists.

Some other salient aspects of the study are as follows:

- Panelists were provided with the incident classification descriptions and the formwork construction activity descriptions.
- Panelists were asked to provide ratings for the *average* frequency and *average* severity for the industry in general using their expert judgment.
- Panelists were asked to provide frequency and severity ratings considering a scenario where no safety program elements are implemented.
- Panelists were provided with the frequency and severity scales illustrated by Tables 1 and 2.

Results

During the observation phase, 11 worker activities were identified and described. As indicated previously, the activities and descriptions were sent to industry professionals for their review and validation. During this review, the activity descriptions were refined and two additional activities were identified. Table 4 summarizes the findings of the observation phase of the study and includes activity names, descriptions, and approximate exposure. One should note that the risks defined for the activities described in Table 4 apply only to activities that are performed as described. For example, the risk value for ascending and descending a ladder with materials or equipment would likely be different from the activity described in Table 4. This represents a limitation of the study.

The exposure values in Table 4 represent the average percentage of time spent performing a specific activity during an 8-h work day for the four projects observed. One will note the percentages total 6–8% as an average of 14% of the workers' time was on nonproductive activities such as resting, eating, or talking about nonwork related topics. Since these exposures are calculated using only four projects, this information should be used for reference and should not be considered representative of the industry as a whole.

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Table 4. Activity Descriptions and Approximate Exposure (Percent of an 8-h Work Day)

Activity name	Description	Approximate exposure
Ascend/descend ladder	Operations that occur above or below grade typically require workers to ascend or descend ladders to reach the work site. Ladders may be wooden, metal, or fiberglass and vary in length from site to site. In many cases, workers may climb up the formwork supports instead of using a ladder.	3%
Static lift	Workers are often required to temporarily support a portion of the concrete form while other workers connect materials or components. This activity involves a static lift and may be accompanied by lifting/lowering.	6%
Nail/screw/drill	Nailing or screwing form components or materials may involve the use of a hammer (typically larger than 20 oz.), nail gun, electric screwdriver, impact wrench, or staple gun. The worker may be required to repeat this activity for an extended period of time at certain stages of construction.	8%
Motorized transport	Materials may be 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.	2%
Crane materials	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. Workers must direct the crane operator as the material is lifted or lowered and may be required to manually guide the load.	5%
Cut materials	During most formwork operations materials such as 2×4's, plywood, or aluminum must be cut to size. Typically, equipment such as a circulating saw or reciprocating or table saw is used to cut materials and the worker operates such equipment and guides materials during cutting/ripping.	9%
Inspect/plan	During construction workers and crew leaders often take time to inspect their work and plan for subsequent operations or inspect prior work.	16%
Lift/lower materials	Lifting and lowering materials or equipment involves unassisted vertical transport of construction materials, formwork components, or equipment. The process of forming concrete may require that workers lift materials from foot-level to a higher or lower grade.	8%
Manual transport	Manual transport may include transporting equipment and materials of varying weights such as 2×4's, plywood, form panels, ties, cat heads, and adjustable pipe braces, from one location to another.	11%
Hammer materials	This activity is different from nailing components and materials because heavier tools such as a sledgehammer may be necessary to drive large objects. Such an activity typically requires fewer strikes of larger force than standard nailing.	6%
Plumb/level forms	Leveling and plumbing forms involves using bodyweight, pry bars, or other equipment to shift and adjust the formwork. A screw jack may be used for this activity and some workers may be surveying or using hand levels, lasers, or plumb bobs to ensure proper placement.	6%
Excavation	Excavation involves the removal of soil or other materials to access areas below grade. This activity typically involves the use of heavy equipment such as a backhoe or a bulldozer.	2%
Lubrication/preparation	Form lubrication and preparation involves spraying form oil and/or curing compound and setting and wetting curing blankets and expansion materials.	4%

The activity descriptions in Table 4 were provided to the Delphi panel along with the 10 risk classification codes in a structured Delphi survey. During the Delphi process, panelists were asked to provide 130 frequency ratings and 130 severity ratings (13 activities $\times$ 10 safety risk codes). In total, the expert panel provided over 10,000 ratings during the course of three rounds. To define the level of consensus, the absolute deviation was tracked and averaged for frequency and severity. The degree of consensus of each round is summarized in Table 5. The target consensus of an absolute deviation of less than one unit on a 1–10 scale was achieved after the second round. However, a third round was completed, because of the compelling reasons given for outlying responses. After three rounds the absolute deviation was 0.38 and 0.49 units for frequency and severity, respectively. The average deviation for all ratings was 0.435 units. The writers believe that this level of consensus is sufficient for this study due to the complex nature of the research, the confounding factors that lead to safety risk ratings, and the variability in experiences among safety experts.

When analyzing the data, the frequency ratings were converted from a range of values with units of worker-hours per incident to a single point-value with units of incidents per worker-hour. The conversation involved finding the mean value in the frequency range and inverting this value to obtain a number with appropriate units. For example, if the Delphi panel rated the average frequency as 100–1,000 w-h/incident, the mean value, 550 w-h/incident, was identified and the inverted value, 0.0018 incidents/w-h, represented the frequency value for that particular risk and activity. These values were converted to facilitate risk quantification and interpretation. Severity values were not altered beyond their interpretation on the severity scale in Table 2.

The frequency ratings ranged from 0 to 0.018 incidents per

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Table 5. Consensus during Delphi

Round	Absolute deviation from the median: Frequency ratings	Severity ratings
1	1.57	1.86
2	0.59	0.71
3	0.38	0.49

worker-hour and the severity ratings ranged from 2 to 1,024 units on the severity scale. The product of the frequency and severity ratings represents the unit risk for the activities. For example, the frequency value was multiplied by the severity value for falls to lower level when ascending or descending a ladder to determine the risk value. A summary of quantified risks can be found in Table 6. In this table, risk is described in terms of units of severity per worker-hour (S/w-h). The element of exposure was not included as a part of this analysis because it is highly project-dependent.

One should note that all of the risk values obtained through the Delphi process are limited in the following ways due to the specific directions given to the Delphi panelists:

- The values represent the average for all firms in the industry regardless of size, geographic location, safety record, etc.
- The risk values represent average risk levels that would occur if no safety programs are implemented.
- The risk values represent the judgment of safety experts and do not represent empirical data.
- The risk values are generic and do not account for extreme or unusual project conditions or organizational cultures.

Analysis

The data matrix in Table 6 can be used to describe several unique aspects of risk during the process of forming concrete. For example, the data can be used to determine the total safety risk for each of the classification codes for any combination of activities. Table 7 summarizes the quantified risks when all formwork activities are included. The highest safety risks for the construction of concrete formwork is exposure to harmful substances (18.62 S/w-h), fall to lower level (1.88 S/w-h), and struck-by (0.96 S/w-h). The lowest risk level belongs to the "Other" category which accounts for only 0.000 00016 S/w-h.

Table 7. Comparison of Risk Values among Safety Risk Classification Codes

Safety risk classification code	Risk value (S/w-h)
Exposure to harmful substances	18.62
Fall to lower	1.88
Struck-by	0.96
Transportation accidents	0.51
Overexertion	0.17
Caught-in	0.08
Struck-against	0.06
Fall to same	0.05
Repetitive motion	0.02
Other	0.00
Total	**22.63**

Further analysis of the data was conducted to determine the highest risk activities associated with the construction of formwork. The risk value for each safety risk code was summed to determine the total safety risk score for each activity. The results of this analysis are presented in Table 8. The data indicates that form lubrication and preparation (18.67 S/w-h), ascending and descending ladders (1.86 S/w-h), accepting and loading materials from a crane (0.51 S/w-h), and motorized transport (0.48 S/w-h) are the highest risk activities. The lowest risk activities include inspection and planning (0.01 S/w-h), static lifts (0.03 S/w-h), and nailing, screwing, or drilling form components (0.03 S/w-h). The total risk demand for the construction of concrete formwork, considering all activities, is 22.63 S/w-h.

The data collected in this study was validated using four project case studies with work crews that were dedicated to formwork construction. In these case studies, task durations were measured in terms of worker-hours for crews that were actively constructing formwork. The unit risk values in Table 7 were multiplied by the exposure and the sum of all risks for the work period represented the total risk. At the end of each 4-h work period, workers were asked to identify the frequency of injuries associated with specific severity levels. These values represented the risk perception of the workforce. To validate the data, the total

Table 6. Risk Scores [Severity per Worker-Hour (S/w-h), $n=13$, and $r=3$]

	Struck-by	Struck-against	Caught-in	Fall to lower	Fall to same	Overexertion	Repetition motion	Exposure	Transportation	Other
Ascend/descend ladder	1.2×10^{-4}	1.2×10^{-5}	5.8×10^{-6}	1	1.2×10^{-4}	1.5×10^{-5}	1.5×10^{-6}	7.3×10^{-8}	1	1
Static lift	2.3×10^{-3}	1.2×10^{-2}	1.2×10^{-3}	2.3×10^{-4}	5.8×10^{-4}	1.2×10^{-2}	2.9×10^{-6}	1.5×10^{-7}	5.8×10^{-7}	7.3×10^{-8}
Nail/Screw/drill	2.3×10^{-2}	1.2×10^{-3}	1.2×10^{-4}	2.3×10^{-4}	1.2×10^{-3}	5.8×10^{-4}	5.8×10^{-3}	2.9×10^{-7}	1	7.3×10^{-8}
Motorized transport	4.7×10^{-3}	2.3×10^{-3}	2.3×10^{-3}	2.3×10^{-4}	1.2×10^{-4}	5.8×10^{-6}	2.9×10^{-7}	7.3×10^{-8}	4.7×10^{-1}	1
Crane materials	4.7×10^{-1}	2.3×10^{-2}	2.3×10^{-2}	2.3×10^{-4}	1.2×10^{-3}	2.9×10^{-5}	1.5×10^{-6}	7.3×10^{-8}	5.8×10^{-5}	7.3×10^{-8}
Cut materials	4.7×10^{-2}	2.3×10^{-3}	1.2×10^{-3}	5.8×10^{-7}	2.9×10^{-5}	5.8×10^{-5}	5.8×10^{-5}	1.5×10^{-6}	1	1
Inspect/plan	2.3×10^{-4}	1.2×10^{-4}	1.2×10^{-5}	4.7×10^{-3}	1.2×10^{-3}	1.5×10^{-6}	1.5×10^{-7}	1.5×10^{-7}	5.8×10^{-7}	1
Lift/lower materials	1.2×10^{-1}	5.8×10^{-4}	1.2×10^{-3}	2.3×10^{-4}	1.2×10^{-2}	5.8×10^{-2}	5.8×10^{-3}	1.5×10^{-7}	1.2×10^{-6}	1.5×10^{-7}
Manual transport	1.2×10^{-4}	1.2×10^{-4}	1.2×10^{-4}	2.3×10^{-4}	1.2×10^{-2}	2.3×10^{-2}	5.8×10^{-4}	1.5×10^{-7}	5.8×10^{-5}	1
Hammer materials	2.3×10^{-1}	1.2×10^{-3}	5.8×10^{-6}	1.2×10^{-6}	1.2×10^{-3}	1.2×10^{-2}	5.8×10^{-4}	1.5×10^{-7}	1	1
Plumb/level forms	2.3×10^{-2}	1.2×10^{-2}	2.3×10^{-3}	4.7×10^{-3}	5.8×10^{-3}	5.8×10^{-2}	5.8×10^{-4}	1.5×10^{-7}	1	1
Excavation	4.7×10^{-2}	4.7×10^{-3}	4.7×10^{-2}	2.3×10^{-3}	1.2×10^{-2}	5.8×10^{-4}	5.8×10^{-6}	2.9×10^{-6}	1.2×10^{-5}	1
Lubrication/preparation	5.8×10^{-7}	5.8×10^{-7}	5.8×10^{-7}	4.7×10^{-3}	1.2×10^{-5}	1.2×10^{-3}	1.2×10^{-3}	1.9	4.7×10^{-2}	1

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Table 8. Comparison of Risk Values among Formwork Construction Activities

Formwork construction activity	Safety risk score (S/w-h)
Lubrication/preparation	18.67
Ascend/descend ladder	1.86
Crane materials	0.51
Motorized transport	0.48
Hammer materials	0.25
Lift/lower materials	0.19
Excavation	0.11
Plumb/level forms	0.11
Cut materials	0.05
Manual transport	0.04
Nail/screw/drill	0.03
Static lift	0.03
Inspect/plan	0.01
Total	**22.63**

risk values were compared with the risk perceptions. The data correlated with an *r*-value of 0.72 which is relative high given the subjective nature of the worker's risk perceptions. The specific process implemented to validate this research will be discussed in detail in a subsequent publication.

Application

The risk values presented in this paper may be used by the construction industry in several ways. First, the data can be used to identify the relative magnitude of safety and health risks associated with specific activities. For example, a safety manager could use the results of this study to improve the effectiveness of job hazard analyses by indicating the relative risk and a subjective interpretation (high, medium, or low risk) for each task. The effectiveness of these forms would be improved because one could highlight the extreme safety risk associated with form lubrication and preparation. Furthermore, the specific risk of exposure to harmful substances when preparing and lubricating forms could be noted. Last, these relative risk values could be used to focus inspections, toolbox talks, and training on high-risk tasks and reduce emphasis on low risk tasks.

The second major application of these risk data involves evaluating the safety risk impact of alternative means and methods of construction. For example, if a manager wanted to objectively consider the safety impact of three methods of formwork construction (e.g., traditional, slip forming, and panelized forms), the manager could use the unit risk data provided in this paper along with expected task durations associated with each method to compare the safety impact of each alternative. This would allow safety to be considered along with traditional project metrics such as schedule, budget, and quality.

To illustrate this application the writers have provided a hypothetical example in Table 9. In this table one can see that there are three options of formwork construction: traditional, panelized, and slip forms. Exposure (i.e., duration) estimates for the three alternatives have been provided for each required activity. The exposure values have been provided in units of worker-hours to maintain consistency. The cumulative risk, in units of severity, is calculated for each alternative using Eq. (3). As one can see from this example, traditional formwork has the lowest risk impact (1,366 S) and slip forming has the highest safety impact (2,004 S). One should note that these values are contingent upon the expected exposure levels. Therefore, the accuracy of this analysis depends largely on the user's ability to accurately estimate task durations.

If implemented, this analysis technique could be used to objectively evaluate the potential impact of each alternative on site safety for formwork based upon estimated exposure durations for expected work activities and the unit risk data provided in this paper (Table 8).

Conclusions

This paper offers a unique method of risk quantification that includes all types of safety and health risks. By defining risks based upon worker activities rather than outcomes, the writers believe that safety programs may be better-designed to target high-risk activities. The concept and methods associated with risk demand quantification presented in this paper can be used to quantify, model, and manage safety risk for any construction process. The

Table 9. Evaluation of Alternative Means and Methods of Construction

Formwork activity	Unit risk (S/w-h)	Traditional formwork construction w-h	Traditional formwork construction Risk (S)	Panelized formwork w-h	Panelized formwork Risk (S)	Slip forming w-h	Slip forming Risk (S)
Lubrication/preparation	18.67	18	336	36	672	45	840
Ascend/descend ladder	1.86	180	335	180	335	180	335
Crane materials	0.51	90	46	720	367	900	459
Motorized transport	0.48	540	259	180	86	180	86
Hammer materials	0.25	360	90	180	45	180	45
Lift/lower materials	0.19	720	137	540	103	540	103
Excavation	0.11	360	40	360	40	360	40
Plumb/level forms	0.11	270	30	450	50	450	50
Cut materials	0.05	540	27	90	5	90	5
Manual transport	0.04	540	22	90	4	180	7
Nail/screw/drill	0.03	900	27	540	16	540	16
Static lift	0.03	360	11	540	16	450	14
Inspect/plan	0.01	720	7	540	5	540	5
	Total	5,598	1,366	4,446	1,743	4,635	2,004

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data presented can be used to identify the high-risk activities that occur during formwork construction and to guide safety managers in their efforts to reduce safety risk associated with this process. For example, the data suggests that targeted risk reduction may be necessary for high-risk activities such as form lubrication and preparation.

Formwork construction was selected and highlighted in this manuscript because literature and OSHA statistics indicate that the process involves a high rate of severe construction accidents and because the process is involved in nearly every construction project. In order to determine the safety risk demand of the process of constructing formwork, the specific construction activities and the potential safety risks needed to be identified and described. Using a total of 256 w-h of field observation a preliminary primary list of worker activities and corresponding descriptions was created. This preliminary list was reviewed, augmented, and validated by a group of eight individuals with an average of approximately 20 years of experience. The result was a final list of 13 distinct and well-defined activities.

Once the activities were defined and appropriate risk classifications were created using data from three major sources, the Delphi process was implemented in an effort to quantify the frequency and severity components of safety risks associated with each activity. The Delphi process was specifically designed for this study using guidance from literature. Additionally, forms of judgment-based bias were identified from social psychology literature and techniques such as randomization, feedback, and anonymity were implemented during the Delphi process in order to minimize these biases.

The resulting data matrix from the Delphi survey was presented and converted to useable units of frequency, severity, and risk. The subsequent analysis indicated that the highest risk activities include the application of form oil, lifting and lowering form components, and accepting materials from a crane. Considering all formwork activities, the highest safety risks were exposure to harmful substances, struck-by, and overexertion.

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