Quantification and Assessment of Safety Risk in the Design of Multistory Buildings

Vineeth Dharmapalan[1]; John A. Gambatese, M.ASCE[2]; Joe Fradella[3]; and Ali Moghaddam Vahed, S.M.ASCE[4]

Abstract: Research has shown that construction worker safety and health is influenced by the design of the permanent structure being constructed. Architects and design engineers have the opportunity to positively affect construction worker safety and health through the choices they make in the design process. Lack of designer knowledge about construction processes and limited availability of tools to assist in assessing the safety risk associated with a design are considered as inhibitors to implementation of the design for construction safety (DfCS) concept. This paper presents research conducted to quantify the construction safety risk of each of the design elements present in typical multistory buildings in the United States. The major research efforts were (1) identification of the typical building design elements and associated construction activities; (2) quantification of the unit and cumulative risks of the design elements and construction activities; and (3) development of an online design risk-assessment tool. Absolute safety risks were quantified for 141 design elements and 683 construction activities using the survey-analytical research method. The risk factors developed were incorporated into an online tool titled Safety in Design Risk Evaluator (SliDeRulE). The research contributes to the construction industry body of knowledge by providing quantitative values that link specific design features to construction safety. The website is designed to assist building designers with assessing the level of construction safety risk associated with their designs and is intended for use by designers during the design phase to create buildings that are safer to construct. **DOI: 10.1061/(ASCE)CO.1943-7862.0000952.** *© 2014 American Society of Civil Engineers.*

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Introduction

The construction industry statistically remains one of the most dangerous industries (Baradan and Mumtaz 2006; Carter and Smith 2006; Imriyas et al. 2007; CPWR 2013) with the construction site being a very hazardous environment for workers. In 2011, the construction industry employed approximately 7% of the total U.S. workforce, yet accounted for 15.7% of the fatalities [Bureau of Labor Statistics (BLS) 2013a] and 5.1% of disabling injuries (BLS 2013b). Despite the importance given to safety and the increased safety and health-management activities adopted on construction sites, the construction sector is consistently among the major industries with high rates of workplace injuries and fatalities. The construction industry is beginning to realize that the safety practices of the constructor during construction alone are reactionary in nature, by necessity, and inadequate to ensure worker safety. Research studies are increasingly focusing on proactive safety-management strategies and their importance in controlling potential hazards (e.g., Rajendran and Gambatese 2009). One such proactive safety-management strategy that can be adopted during the preconstruction phases is designing for construction safety (DfCS), also referred to as prevention through design (PtD) by many personnel in the construction industry.

Studies have confirmed that a facility's design is one of the contributing factors that influence the safety hazards present during construction (Behm 2005; Driscoll et al. 2008; Jeffrey and Douglas 1994; Lorent 1991). Architects and design engineers can supplement site safety efforts by addressing safety in their designs (Weinstein et al. 2005). However, the U.S. construction industry has been slow in adopting DfCS for a variety of reasons. Lack of designers' knowledge about construction processes, difficulty in assessing the safety risk associated with a design, and limited availability of DfCS tools are examples of inhibitors to the development and implementation of DfCS (Gambatese et al. 2005).

The primary objectives of the research presented in this paper are to further understand the safety risk associated with building designs and to educate designers regarding the construction processes related to their design decisions and the safety hazards present during the construction of their designs. To achieve these objectives, a structured survey of construction site personnel was conducted and a tool to evaluate typical design features of multistory buildings was subsequently developed based on the survey findings. The research encompassed all of the major systems that make up a multistory building (foundation, structural framing, exterior enclosure, interiors, roofing, HVAC system, electrical, plumbing, and fire suppression), and each of the different design components/features that make up these systems. The evaluation of the design features is based on safety risk ratings calculated by obtaining estimated risk values associated with the process for constructing the design features. The design rating system developed serves as a DfCS tool for designers and also provides an opportunity

[1]Project Engineer, Project Baseline Consultants, C-11, C-Wing, Ground Floor, Satyam Shopping Center, M.G. Rd., Ghatkopar—East, Mumbai 400077, India. E-mail: d.vineeth@gmail.com

[2]Professor, School of Civil and Construction Engineering, Oregon State Univ., 101 Kearney Hall, Corvallis, OR 97331 (corresponding author). E-mail: john.gambatese@oregonstate.edu

[3]Instructor, School of Civil and Construction Engineering, Oregon State Univ., 101 Kearney Hall, Corvallis, OR 97331. E-mail: joe.fradella@oregonstate.edu

[4]Graduate Student, School of Civil and Construction Engineering, Oregon State Univ., 101 Kearney Hall, Corvallis, OR 97331. E-mail: moghadda@onid.oregonstate.edu

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to rate projects based on the priority given to designing for construction safety. It is expected that the results of this research will be used by architects and design engineers to make projects safer to construct.

Literature Review

Given the aims and nature of the research study, literature that focused on construction safety risk and risk quantification was explored and used to guide the development of the survey and the risk quantification process.

Construction Safety Risk

The identification and calculation of safety risk associated with construction processes and activities have been investigated for some time. The New York State Division of Industrial Service used workers' compensation rates to determine the degree of risk associated with construction activities (Knab 1978). Everett (1999) analyzed the ergonomic risks associated with 65 construction processes. Using expert opinion and judgment, Jannadi and Almishari (2003) developed a model to estimate the total safety risk on construction sites by considering the risk assessment of major construction activities, equipment, hazardous substances, and external stimuli. Lee and Haplin (2003) used a fuzzy logic system based on expert input to predict the accident risk of common construction processes. Carter and Smith (2006) created a tool (Total-Safety) for improving the hazard identification of projects using an activity-based risk-assessment process. A part of the study by Imriyas et al. (2007) involved estimation of the project hazard index (PHI). The PHI researchers focused only on the most hazardous activities and rated the physical characteristics (height, volume, material, type) of each activity. Hallowell (2008) developed a risk-based construction safety and health analytical model for quantification and mitigation of risk for construction processes. Hallowell's model was subsequently used to estimate activity risk for the concrete formwork construction process (Hallowell and Gambatese 2009). Rozenfeld et al. (2010) assessed the probability of occurrence of potential loss-of-control events for 14 common construction activities of a typical multistory building project. Recently, Mitropoulos and Guillama (2010) analyzed construction activities to determine the high-risk activities for residential construction using claims costs, incident types (i.e., fall from elevation, struck by), and data from a large residential framing contractor.

Very few research studies have evaluated the safety risk of design features. Researchers in Australia have developed a tool to assess the risk of falls during maintenance work on roofs (Cooke et al. 2008). In the study, the risk was not estimated based on construction activities but by using the physical characteristics (area, angle, loadings) of the roof design. The assessment of design features based on safety risk of the associated construction processes has also been performed. In the Netherlands, Frijters and Swuste (2008) devised a risk-assessment model that assesses the risk of hazard events during the construction of design features. The risk classification, however, is based on subjective, nominal scales such as insignificant, acceptable, moderate, unacceptable, and insignificant. Likewise, a recent study in Spain by Gangolells et al. (2010) used risk events to evaluate the safety risk of constructing residential design features. The authors focused only on the high-risk activities for estimating the risk, and also an expert panel of associate professors, architects, engineers, and project managers was used for the risk-assessment of construction activities.

Safety Risk Quantification and Analysis

Traditionally, construction safety risk has been defined using multiple factors, namely frequency, severity, and exposure. Over the years, researchers have developed several different methods to quantify and analyze safety risk. The research also varies in terms of the methodology used to obtain the risk data for assessment (i.e., qualitative or quantitative) and the scales of measurement. The definition, quantification, and scales of measurement of the factors in some of the recent studies are summarized below.

Baradan and Mumtaz (2006) used statistical injury and fatality data from the U.S. Bureau of Labor Statistics (BLS) website for estimating the risk associated with different construction trades. In the study, frequency was calculated as the annual injury and fatality rate using the level of annual employment. The cost of lost time due to an injury for a given trade was used as the measure of severity, and the cost was calculated using the median number of days away from work, hourly wage, and number of hours worked in a day. Frijters and Swuste (2008) determined the safety risk of construction activities using probability and severity. Exposure to the risk was calculated using man-hours per unit of the design feature and total amount of the design feature under consideration. Gangolells et al. (2010) used probability and severity to determine significance of the risk to shortlist the high-risk activities, and the sum of all potential exposures for a project was used to evaluate the risk of a project. Exposure is defined as project dependent and is a measure of the extent of the hazardous situation (unsafe condition). Hallowell and Gambatese (2009) created objective risk scales that account for all possible frequency and severity levels. Hallowell and Gambatese define frequency in terms of worker hours per incident and severity in terms of impact to the worker. They also define exposure in terms of worker-hours, which is identified as project dependent.

Research Contribution and Significance

The design of the current study is in direct response to the findings and recommendations of past research studies. Design features and materials influence construction means and methods to a large extent (Gambatese 2000; Gambatese et al. 2003), and hence knowledge of the individual construction tasks, sequencing between tasks, and coordination of different trades and their processes help in creating designs that are safer to construct (Toole 2005). The current study addresses the designer lack of knowledge barrier by incorporating a construction activity level evaluation of the design features. Further, Gambatese (2008) recommends the need to establish a connection between design features and occupational injuries and illnesses. The tools and technologies currently available are typically hazard specific, i.e., they provide information about construction site hazards as a result of the designs or design decisions. Additionally, most of the current tools and technologies do not make decisions based on risk-assessment procedures (Gambatese 1998, 2000). Those that do, utilize a subjective, rather than quantitative, level of assessment. Therefore, there is a need for quantification of safety risk and also comparison of the different design alternatives based on the risk assessment (Gambatese 2004; Hinze et al. 1999). In addition, the frequency and severity of injuries need to be considered while deciding on design alternatives (Gambatese 2008). The present research fills these gaps by developing a quantitative risk assessment of design features based on incident frequency and severity.

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Methodology

The research presented in this paper addresses two main research questions: (1) what are the major construction activities undertaken for the typical design elements of a multistory building; and (2) what are the safety risk values associated with the design elements when constructed using the major construction activities. A coupled field survey-analytical research methodology was employed to attain the research objectives. This methodology was adopted owing to the absence of archival data and nonfeasibility of utilizing empirical data. The field survey program included the development of survey questionnaires followed by data collection.

Design of Survey Questionnaires

Questionnaire development began with an inventory of design features and construction activities for multistory buildings. This initial task entailed identifying all of the different design features present within a typical commercial office building, including all of the different design options for each feature, and the major activities performed on a jobsite to construct each design option. Field observation of each construction process was unrealistic for the present study since it would have entailed observing construction activities for multiple design elements for every building system. Therefore, owing to time constraints, limited availability of ongoing projects, and lack of available literature, a different approach was employed to create an initial list of design elements. Building construction books and project schedules provide information on the various systems, typical design features used for each system, and major construction activities performed to construct the design features. Multiple publicly available books on building construction were reviewed to obtain contemporary and comprehensive information (Allen and Iano 2004; Andres and Smith 2004; Dagostino and Wujek 2005; Koel 2005; Mehta et al. 2010). Design elements and related construction activities common to all of the books were recorded and organized. The lists were verified using the researchers' own construction experience, comparison to example construction schedules, and site visits to several ongoing construction projects. In addition, as part of the pilot test of the survey, several survey participants were asked to review and refine the lists of design elements and worker activities. Modifications to the lists were made based on the input received.

Based on the review of the literature, a total of 141 design elements and 683 construction activities were identified and documented. This inventory was then subdivided into fourteen groups according to trade expertise, namely piling, concrete, steel, precast, glazing, masonry, cladding, interior ceilings and walls, flooring, roofing and sheet metal, electrical, heating, ventilation, and air-conditioning (HVAC), plumbing, and fire suppression.

To develop frequency and severity scales for calculating safety risk, the frequency and severity categories developed by Hallowell and Gambatese (2009) were considered for the present study. The frequency scale ranges from 1 incident every 6 min (0.1 worker hours) to 1 incident every 100 million or more worker hours. The severity scale includes a spectrum of 12 possible injury categories from negligible injury (severity = 1) to fatal injury (severity = 26,214). The questionnaires were developed using these scales along with the inventory of design elements and construction activities.

Three general contracting superintendents pilot tested the questionnaires with regard to the shell of a building. Also, one individual in each of the mechanical/electrical disciplines (fire suppression, plumbing, HVAC, and electrical) pilot tested the respective questionnaires. Pilot testing revealed that 12 severity categories were too many to evaluate reliably and prevented thoughtful judgment. Also, the frequency scale in terms of worker hours per incident was confusing to those surveyed. Based on the input received from the pilot testing, the frequency and severity scales were revised and the questionnaires modified. The frequency scale was simplified by defining the average time between incidents in terms of hours, days, and weeks and is shown in Table 1. This frequency scale was used in the present study.

The injury severity levels were categorized based on the worker's ability to return to regular work. This resulted in combining the severity levels used by Hallowell (2008) into four more general severity categories identified as: near miss, low severity, medium severity, and high severity. The severity categories used in the present study and the corresponding combined severity levels from Hallowell (2008) are shown in Table 2.

Survey questionnaires were developed for each building system (i.e., structural framing, roofing, exterior enclosure) as well as construction trade expertise. The general format of all of the questionnaires remained the same despite these divisions. All of the questionnaires started with a similar instruction page describing how to complete the survey, the frequency scale to be used, and the severity categories and definitions. General demographic information about the participant was solicited. Respondents were asked to conduct the following tasks to complete the questionnaires: (1) for each design feature being reviewed, refine the list of construction activities if needed; (2) indicate the typical percentage of time required on each activity within the overall process to construct the design feature; (3) for each construction activity, identify the frequency (i.e., average amount of time) with which injuries at each severity level (near miss, low severity, medium severity, and high

Table 1. Revised Frequency Scale

Average amount of time between incidents	Questionnaire entry by survey participants
Impossible	0
Negligible	1
50 years	2
10 years	3
5 years	4
1 year	5
6 months	6
1 month	7
1 week	8
1 day	9
1 h	10

Table 2. Revised Severity Categories

Injury severity categories (Dharmapalan 2011)	Combined severity levels (Hallowell 2008)
Near miss (no injury or impact on work time)	Near miss Negligible
Low severity (no impact on work time; worker returned to regular work within 1 day)	Temporary discomfort Persistent discomfort Temporary pain Permanent pain Minor first aid
Medium severity (worker could not return to regular work within 1 day)	Major first aid Medical case Lost work time
High severity (worker could not return to regular work at all)	Permanent disablement Fatality

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severity) occur on a project; and (4) for each design feature, indicate any special design features that increase or decrease the safety risk.

The survey method chosen is susceptible to different types of bias that could impact the results. Types of bias that could exist as a result of the particular survey performed include: contrast effect (Bjarnason and Jonsson 2005), neglect of probability (Martin 2006), Von Restroff Effect (Krimsky and Golding 1992), and the serial position effect (Coleman 2006). Multiple measures were implemented to control for biases in the survey responses and their effect on the resulting risk factors. These control measures were the survey questionnaires were structured such that probability and severity values are entered separately; consistent instructions (both written and oral) on how to complete the questionnaire were provided by the researchers to each participant prior to their completing the questionnaire; results are based on an aggregate of multiple responses; companies were randomly selected to participate in the study; responses were solicited from workers employed within different companies, with different years of experience, and who have worked on different projects; and analyses are conducted using median and variance values.

Data Collection

Past studies (e.g., Hinze and Gambatese 2003; Weinstein et al. 2005) have revealed the importance of the trade contractor input in making safer designs. Therefore, the specific personnel targeted to complete the questionnaires were superintendents and safety managers within general contracting (GC) firms and site personnel within trade contracting firms. It was believed that since these personnel work on the jobsite and/or directly with the design features, they have the best experience with constructing the design features and have knowledge of the associated safety risk. The personnel in GC firms were given all of the questionnaires to complete, while the trade contracting personnel were given only the questionnaire(s) related to their trade(s). While it was anticipated that the GC firm personnel might be able to complete all of the questionnaires, they were instructed to complete only those portions for which they felt they had sufficient expertise (i.e., firsthand knowledge of the specific construction activities and the probability of injury associated with each activity).

A convenience sample of GC and trade contracting firms in the Pacific Northwest was drawn from regional construction firm directories. To increase participation in the research, those selected were firms that are located within the state of Oregon and that also have an affiliation with the researchers' institution. To supplement the trade contractor list, the GC firms that participated in the research were also asked to suggest specific trade contracting firms to include in the sample. Overall, only those firms that work on multistory commercial office buildings were included. From this convenience sample, random samples composed of 20 GC firms, 21 mechanical and electrical contractors (HVAC, electrical, plumbing, and fire suppression), and 50 trade contractors (five trade contractor firms per trade) for the remaining trades were drawn and included in the study.

The researchers contacted the 20 GC and 71 trade contracting firms via e-mail and telephone to describe the research study and solicit their participation. In addition, in-person meetings were conducted with some of the firms to further explain the research, solicit their input, and instruct each participant on how to complete the questionnaires. The instruction on how to complete the questionnaires proved important to ensure valid and complete responses and to eliminate bias. The participants were asked to provide their responses using their own personal experience and judgment and not based on the company's safety record.

Results

A total of 15 responses were received from the 20 GC firms contacted, resulting in a response rate of 75%. The mechanical and electrical construction industry professionals returned 15 completed responses out of the 21 sent, for a response rate of 71%. The response rate from the trade contractors representing the other 10 trades was 78% (39 out of 50). The number of responses per trade varied from three to five firms (mean = 3.9). The experience of the respondents was of utmost importance because the risk data was based on an individual's perception. On average, the respondents had 24 years of experience in the building construction industry (ranging from three to 60 years). Other respondent demographics include the following:

- 41 (60%) of the respondents were construction superintendents;
- Other respondents included safety managers (22%), project engineers (9%), project managers (4%), laborers (3%), and a risk manager (1%); and
- Many respondents have had experience working in other positions in addition to their current position, such as: foreman, carpenter, electrician, laborer, and installer.

Amount and type of field experience were considered the most important respondent qualities for the present study. Those with a minimal duration of experience and those with limited construction field experience were believed to not possess sufficient knowledge of the construction process and sensitivity to the safety risks involved. In addition, given their educational background and work perspective, safety managers were assumed to generally have a greater focus on safety hazards as opposed to getting the work done (activities). However, because most of the respondents had some experience in other work positions (e.g., foreman, superintendent), the nature of the respondent's current position was not considered to be a significant limitation of the research study.

While completing the questionnaire, each respondent was asked to verify whether the listed design feature is commonly used and to review and refine the list of activities created for that design feature. The respondents were given the opportunity to expand or combine the listed activities or add/remove activities. Comments and suggestions regarding the listed activities that were made by two or more respondents were considered for inclusion. If additional activities were added, the other participants were subsequently asked to rate these additional activities. In some cases, the respondents also indicated unique aspects of the design features that result in a significant increase or decrease in safety risk.

An example response from one of the respondents for cast-in-place (CIP) concrete columns is shown in Fig. 1. As shown in the figure, CIP concrete columns require five major construction activities to be performed during construction. The activity exposure field shows the average percentage values of time spent by a crew performing the different activities. For example, as per the respondent, a crew takes 30% of the time for formwork construction, 10% for pouring concrete, and so forth. For the four severity fields, the respondent has provided the average duration between incidents (using the frequency scale) for each activity. For example, for stripping of formwork, a near miss happens approximately once every five years, low severity and medium severity incidents occur once every year, and high severity is negligible.

Similar numerical responses were received from the survey respondents for all the design elements. Following receipt of the participant responses, the data was aggregated and the median for each of the exposure and frequency values was calculated. Reporting the median response values minimizes judgment-based bias and the variation in responses (Hallowell 2008). Further analysis of the numerical responses revealed that the average standard deviation

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SYSTEM/ COMPONENT :COLUMNS							
DESIGN FEATURE/ ELEMENT: CAST IN PLACE CONCRETE COLUMNS							
ACT. NO.	ACTIVITY EXPOSURE*(%)	ACTIVITIES	ACTIVITY DESCRIPTION	INJURY SEVERITY LEVEL			
				Near Miss	Low Severity	Medium Severity	High Severity
1	30%	Connection of foundation dowels with column rebar	hoisting of column reinforcement cage over foundation dowels, overlapping/ splicing and tying of the vertical rebar of columns and foundation dowels	4	5	3	1
2	30%	Formwork construction for columns	cutting, lubricating, hoisting, placing, bracing, connecting and leveling are some of the sub-activities performed during this activity	5	5	3	1
3	10%	Pouring of concrete for columns	concrete is poured using pumps/ buckets and consolidated using vibrators	5	5	5	1
4	20%	Stripping of formwork	stripping of the column formwork after it gains sufficient strength	4	5	5	1
5	20%	Repair and patching work after stripping of formwork	repairing of irregularities or defects in the cast columns such as honey-combing or segregation using mortar	2	3	2	1

Frequency Scale: Average amount of time between incidents										
Impossible	Negligible	50 years	10 years	5 years	1 year	6 months	1 month	1 week	1 day	1 hr
0	1	2	3	4	5	6	7	8	9	10

Fig. 1. Example questionnaire response

for the collective responses of the activity exposure was 4.19 and for the injury severity levels was 1.54. The high variability in the injury severity level may be attributed to the difference in risk perception between general and trade contractors (Dharmapalan and Gambatese 2012). A trade contractor specializes in his/her own trade and has complete knowledge of it. A general contractor on the other hand supervises the entire project and a trade contractor's work is part of his/her supervision. Outlying response values by one respondent (who indicated 100% for each of the exposure values for all activities of every design feature) also contributed to the high variability in the activity exposure field. With these outlying response values removed, the mean standard deviation of the remaining responses reduces from 4.19 to 2.02 for the activity exposure and from 1.54 to 1.53 for the injury severity levels.

Analysis

The analytical program for the research study involved the calculation of unit risk and cumulative risk factors of all the design elements and the associated construction activities. As a first step, the relative weights of the four severity categories were quantified. Following this step, the median frequency and median percentage activity exposure values were converted into usable units. These calculations were followed by a risk analysis where the unit risk and cumulative risk of design elements are calculated.

The present study consisted of four severity categories after combining the relevant injury types of the severity scale developed by Hallowell and Gambatese (2009). The impact value of the injury types presented by Hallowell and Gambatese (2009) represented a geometric scale ranging from 1 (negligible injury) to 26,214 (fatality). It was required to find the impact values for the four severity categories that were representative of each severity category as well as reflective of the geometric progression. A graph was prepared on which the linear scale (discrete) values were plotted on the x-axis and the corresponding geometric impact (continuous) values on the y-axis. The interpretation and calculation resulted in an equation equivalent to weighted averages given by Eq. (1)

$$Y = \frac{\sum_1^n x_i y_i}{\sum_1^n x_i} \tag{1}$$

where x_i represents the linear scale value and y_i represents the corresponding geometric scale value. For example, for the low severity (LS) category, Eq. (1) along with the linear and geometric values shown in Table 3 were used to compute the impact value as follows:

$$Y_{LS} = \frac{(1 \times 2) + (2 \times 4) + (3 \times 8) + (4 \times 16) + (5 \times 32)}{1 + 2 + 3 + 4 + 5} = 17$$

Using a similar approach, the weighted averages of the impact values for the medium severity and high severity categories were also calculated and are shown in Table 3. The near miss category has been assigned two values, 0 and 1. A near miss by definition is an accident that does not result in injury or damage. However, it is important to document near misses to reduce reoccurrence and prevent more severe accidents (Hinze 2006). In addition, the focus of the risk evaluation is on hazards, not just injuries and fatalities. Therefore, near misses can be considered as indicators of hazards, and the severity impact is given a value of 1 while performing a hazard assessment and 0 for solely an injury assessment.

The median frequency value aggregated for each activity and severity category were converted from units of worker-hours per incident to units of incidents per worker-hour. Each frequency value on the scale used for the survey corresponds to time periods in either hours, days, months, or years. The median frequency responses were converted to worker-hours assuming an average of 45 worker-hours per week for 50 weeks a year. By finding the inverse

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Table 3. Severity Impact Values

Severity levels (Hallowell 2008)	Linear scale value (Hallowell 2008)	Geometric scale value (Hallowell 2008)	Weighted average value (Dharmapalan 2011)	Injury severity categories (Dharmapalan 2011)
Near miss	0	0	0 and 1	Near miss
Negligible	0	1		
Temporary discomfort	1	2	17	Low severity
Persistent discomfort	2	4		
Temporary pain	3	8		
Permanent pain	4	16		
Minor first aid	5	32		
Major first aid	6	64	158	Medium severity
Medical case	7	128		
Lost work time	8	256		
Permanent disablement	9	1,024	14,282	High severity
Fatality	10	26,214		

Table 4. Frequency Conversions

Frequency scale input value	Original range	Worker-hours per incident	Incidents per worker-hour
10	1 h	1	1.00
9	1 day	9	0.111
8	1 week	45	0.0222
7	1 month	189	0.0053
6	6 months	1,134	0.00088
5	1 year	2,250	0.00044
4	5 years	11,250	0.000089
3	10 years	22,500	0.000044
2	50 years	112,500	0.0000089
1	Negligible	Negligible	0

of these frequency values, the actual frequency values in incidents per worker-hour is calculated. Table 4 shows both the conversion from recognizable work durations to worker-hours and the probability values in terms of incidents per worker-hour.

The median activity exposure values aggregated for each activity from the participant responses were converted to worker-hours per unit of design element. The R.S. Means "Building Construction Cost Data" manual (RS Means 2011) lists the typical man-hours required per unit for construction of each of the design elements commonly included in a building. The man-hours per unit for the design elements selected for the study were documented from the R.S. Means manual. Tables 5 and 6 show examples of the man-hours required to construct footings and foundations. The median percentage exposure values for each activity of a design element were used to distribute the worker-hours per unit to each activity.

The converted frequency values in terms of incidents per worker-hour, the four severity values defined in terms of impact to the worker, and the activity exposure values defined in terms of worker-hours per unit, were then used to calculate the risk values for each activity and each severity category. Unit risk and cumulative risk values corresponding to each activity and each severity category were calculated using Eqs. (2) and (3) as follows:

$$\text{Unit risk}(\text{S/w-h}) = \text{Frequency (incident/w-h)} \times \text{Severity}(\text{S/incident}) \quad (2)$$

Table 5. TUR and TCR for Footings and Foundations

Design feature/element	Units	Worker-hours/unit (w-h/unit)	Total unit risk (TUR) (S/w-h)	Total cumulative risk (TCR) (S/unit)
Steel H-pile	V.L.F.	0.113	0.288	0.016
Steel pipe pile	V.L.F.	0.094	0.498	0.013
Precast concrete pile	V.L.F	0.110	0.682	0.021
Bored concrete pile	V.L.F.	0.133	0.385	0.011
Driven concrete pile	V.L.F.	0.169	0.173	0.009
Pile cap	C.Y.	1.748	0.546	0.205
Drilled shaft/drilled pier	V.L.F.	0.120	0.080	0.002
Drilled caisson	V.L.F.	3.542	0.080	0.051
Isolated column/ spread footing	C.Y.	2.699	0.199	0.110
Wall/strip footing	C.Y.	2.550	0.467	0.229
Mat foundation	C.Y.	2.441	0.671	0.368
Slab-on-ground/ slab-on-grade	S.F.	0.033	0.078	0.001

Table 6. TUR and TCR for Structural Frame Elements

Design feature/element	Units	Worker-hours/unit (w-h/unit)	Total unit risk (TUR) (S/w-h)	Total cumulative risk (TCR) (S/unit)
Structural steel column	L.F.	0.057	2.403	0.020
Steel built-up column	L.F.	0.057	2.270	0.025
CIP concrete square column	C.Y.	13.832	0.916	2.665
CIP concrete round column	C.Y.	8.958	0.922	1.741
Precast concrete column	L.F.	0.556	1.028	0.108
CIP concrete shear walls	C.Y.	4.327	1.333	1.229
Structural steel beam	L.F.	0.074	3.426	0.030
Steel plate girder/built-up girder	L.F.	0.074	1.193	0.010
Precast beam	EA.	3.668	1.112	1.112
One-way solid slab	C.Y.	8.718	1.433	1.599
Two-way solid slab	C.Y.	7.226	1.433	1.325
Flat plate slab	C.Y.	5.140	1.019	0.762
One way joist slab	C.Y.	7.167	1.573	1.260
Two way joist (waffle) slab	C.Y.	5.166	1.573	0.908
Posttensioned beam and slab	C.Y.	8.924	1.517	1.487
Hollow-core plank slab	S.F.	0.023	1.236	0.006
Cellular deck	S.F.	0.056	1.811	0.014
Composite deck	S.F.	0.040	1.777	0.010
Open floor deck	S.F.	0.035	1.632	0.008
Steel form deck	S.F.	0.038	1.632	0.009
Steel roof deck	S.F.	0.011	0.905	0.003

$$\text{Cumulative risk}(\text{S/unit}) = \text{Frequency}(\text{incident/w-h}) \times \text{Severity}(\text{S/incident}) \times \text{Exposure}(\text{w-h/unit}) \quad (3)$$

Unit risk is calculated by multiplying the frequency values of each severity category by the corresponding severity impact value. The summation of the unit risks corresponding to each severity category for an activity (i.e., horizontally along an activity shown in Fig. 1) gives the total unit risk (TUR) associated with the activity for the design feature. The summation of the unit risks along a severity category (for example vertically along the low severity column in Fig. 1) gives the total unit risk for a severity level for the design feature. The total unit risk associated with constructing a design feature is the summation of the calculated total unit risks

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for all of the activities undertaken to construct the design feature, or the summation of the calculated severity categories unit risks.

For computing the cumulative risk values, each calculated unit risk value is multiplied by the activity exposure value defined in terms of worker-hours per unit of the design feature. The summation of the cumulative risks corresponding to each severity category for an activity gives the total cumulative risk associated with the activity for the design feature. The summation of the cumulative risks vertically along a severity category gives the total cumulative risk for a severity level for the design feature. The total cumulative risk (TCR) associated with constructing a design feature is the summation of the calculated activities' cumulative risks for the design feature or the summation of the calculated severity categories' cumulative risks.

Using the calculation procedures described above, the unit risk and cumulative risk factors for all of the 141 design features were calculated. For example, Table 5 shows the risk factors for footings and foundations, and Table 6 shows the factors for structural frame elements. The website described below provides the design risk factors highlighted in Tables 5 and 6 along with the risk factors associated with the remaining design features. It is important to note that directly comparing the TUR (or TCR) values of different design features shown in the tables does not necessarily give an accurate comparison of the safety risk associated with the design features. The risk factors, which are stated in terms of severity per unit, need to be multiplied by the extent to which the design feature is present in the design (i.e., number of units) to obtain the total risk associated with a design feature. The amount of units required for one design feature may be different than that required for a different design feature used for the same purpose (e.g., steel column compared to CIP concrete column). After multiplying by the number of units, the risk associated with each design element can be compared. In addition, different design features may be measured in different units. Hence, a direct comparison of the risk factors may not be appropriate.

For each of the design elements, the researchers also quantified the construction safety risk values for each of the four severity categories and for each construction activity. While not the primary objective and contribution of the present research, analyses of the risk factors developed afford the opportunity to assess differences in risk perception between different project team members. The computed risk factors were further analyzed to compare the risk perception between the three respondent groups (GC superintendents, GC safety managers, and trade contractor personnel) and to compare design alternatives in terms of risk factors. The analysis results were previously reported by Dharmapalan and Gambatese (2012). The results revealed the following significant findings: (1) for the design elements considered, there is no evidence of a difference in risk perception between GC superintendents and GC safety managers for both unit and cumulative risk comparisons; (2) there is no evidence of a difference in the way GC superintendents, GC safety managers, and trade contractors perceive near miss risks; and (3) there is a difference in safety risk perception between general and trade contractors for the majority of the design features. The analysis also focused on several of the 141 design features. With respect to those specific design features investigated, the results revealed the following significant findings: (1) interior partition and exterior backup walls using steel studs are less risky to construct as compared to using CMU blocks; (2) resilient and carpet flooring present less safety risk than stone panel, terrazzo, and raised access flooring; and (3) the risk of accidents resulting in lost work time or hospitalized injury is less for suspended acoustical ceilings as compared to suspended gypsum and cement plaster ceilings (Dharmapalan and Gambatese 2012).

Design Safety Risk Assessment Tool

In addition to quantifying the risk factors, the research effort included the development of an online design assessment tool. The research team programmed a website to incorporate all of the risk factor values and allow designers to input and compare designs based on safety risk. The assessment tool, titled *Safety in Design Risk Evaluator* (SliDeRulE), is available at www.constructionsliderule.org.

The website is structured in a simple format that allows designers to focus on their designs and on the safety risk associated with their designs. For each project being designed, the website prompts users to input the quantities of each of the different design features included in the project (e.g., the number of cubic yards of concrete in a mat foundation or the total linear feet of electrical cable). After all of the design quantities are input, or just those which are of interest to the designer, the website calculates the total safety risk associated with the design. A higher total risk value signifies a design that poses greater safety risk to the construction workers. The website allows the designer to enter different design alternatives (e.g., a structural steel frame or a reinforced concrete frame) to modify and select a design based on safety risk. Additionally, an engineer, for example, can compare the safety risk of a building with a precast concrete frame to that of the same building with a CIP concrete frame. The website also provides examples of particular aspects of the design features that are particularly beneficial or detrimental to construction worker safety.

The extent to which the website has been used was measured using the *Google Analytics* tracking system by monitoring the number of people who visit the SCSH website and their geographical location. In the 12 months since it was placed online in August 2013, the website has had 2,097 visits (approximately 175 visits per month), of which 1,532 were unique visitors (128 per month). In terms of the geographical location, new users from 55 countries visited the website, primarily from the United States (72%), followed by India (4%), Canada (3%), Brazil (3%), Australia (3%), and the United Kingdom (2%). Further research on the extent of use and impact of the website, along with the barriers to and benefits of its use, is recommended to both improve the website and help promote the design for construction safety concept.

Limitations

One factor limiting the ability to generalize the research findings to all construction projects is that the frequency ratings obtained for the study are risk perceptions of construction personnel and not based on empirical data. Additionally, the study samples of general contracting firms and trade contracting firms were randomly selected from convenience samples. Last, while each of the participants were experienced in their trade or field of construction, no efforts were undertaken to qualify them as experts. The aggregated data comes from participants with different levels of expertise. Therefore, the ability to extend the scope of the study to a greater population with confidence is limited. However, because most of the respondents have many years of work experience, and work experience in different regions of the country, the results can be applied to the construction industry in the United States.

Design elements are constructed/prefabricated in all shapes and sizes depending on the characteristics of the project. The results of the study are limited as the risk factors are representative of design elements used only in a typical multistory building (approximately five stories or more) and may not be applicable to all building types. Buildings of this size predominantly include steel and concrete-framed buildings and exclude wood-framed structures,

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light industrial facilities, and smaller commercial buildings. Worker perception of safety risk may vary based on building size or number of stories (i.e., perception of greater risk for taller and/or larger buildings). No literature was found that indicates a difference in risk perception based on building size or height, and this potential bias was not taken into account in the study.

In addition, the design element risk factors apply to the construction activities as identified, defined, and provided to the respondents. In construction, multiple means and methods can be used to perform the same task and hence the risk factors may change if alternate methods or additional activities are employed. Last, the risk data quantified are absolute values. The construction safety risk due to the interaction among activities and due to other external risk factors is not considered.

The SliDeRulE website provides a useful online tool for design professionals. However, given the focus on buildings, applicability of the website is limited to multistory buildings that contain the design elements present in the website. Further research is needed to develop design risk factors for other types of projects (e.g., roadway, bridge, industrial, and light residential).

Conclusions and Recommendations

Currently, there is a lack of data and tools available in the U.S. construction industry that can be used to quantitatively evaluate how safe design elements are to construct in the field. The main objective of the research presented in this paper was to quantify the construction safety risk associated with the construction of design elements used for multistory buildings and develop a tool for industry to use to evaluate the safety risk of designs. To meet this objective, the commonly used design features and the corresponding major construction activities were identified. Using construction literature, a database consisting of building systems, design features, and construction activities was created. Once the design features and activities were identified, survey questionnaires were developed to obtain input from field personnel. The field personnel included general contracting superintendents, general contracting safety managers, and trade contracting superintendents. Field personnel were selected as they are closest to the construction processes of the design elements and hence have better judgment of the construction safety risk. The participants were asked to rate average frequency of incidents for four severity categories associated with each activity for each design feature. The data collected and processed from the survey was presented and converted to useable units of frequency, severity, and exposure. The subsequent analysis resulted in unit risk and cumulative risk matrices for each of the design features selected for the study. The unit risk and cumulative risk matrix for a design feature quantified the risk associated with the activities and risk of the four severity categories for the design feature. The website created for application of the design safety risks provides a tool for architects and engineers to evaluate and modify a design based on construction worker safety risk.

Based on the research results, it can be concluded that risk factors relating each individual design element within a building to the safety of those who construct the design elements can be quantified. To do so, relevant experiential input is required that addresses frequency, severity, and exposure associated with each of the activities required to construct the design elements. Lacking such input will not allow for determining comprehensive risk factors that account for different levels of severity and for different amounts of exposure. In addition, representative frequency and severity scales are needed to convert the input received to the risk factors.

The findings also reveal that risk factors are different from one design element to another. Additionally, depending on the design element, the risk factor may vary between the possible options for each design element (e.g., a different risk factor for steel columns than concrete columns). Using the research methods selected, the calculated risk factors are impacted by the risk perceptions of those surveyed. The analyses reveal that risk perceptions vary between different project personnel. This impact on the final risk values should be taken into consideration when conducting the research and applicable controls should be implemented. Last, based on the research efforts, a tool can be created that allows designers to quantitatively assess the safety risk associated with constructing a design and compare the safety risk between alternative designs.

While the hierarchy of controls indicates that eliminating safety hazards in the design of a project is the preferred method of controlling risk, it is important to note that attempting to do so in practice may not eliminate the need for additional safety controls during construction. That is, all risk cannot be eliminated through the design, and the constructor must implement additional controls. Constructor safety programs can vary significantly as well. Some constructors may be more effective at mitigating risk than others. Therefore, the cost associated with the estimated risk may not be solely dependent on the design. A project designed for safety may still have worker injuries. It is anticipated and expected, however, that the number of injuries and fatalities on projects that have been designed for safety will be less.

One of the major subsequent research efforts required is to validate the results of this study by collecting secondary data. The authors recommend a larger sample size and a formal probability sampling procedure to improve validity. Another future research topic would be to develop a process to allow modification of the risk factors based on site-specific designs or construction conditions (external risk factors). Modification factors would have to be defined for each condition and the values of the modification factors would have to be quantified for the different possible designs or construction conditions. These modification factors would be multiplied by the risk factor values to get the modified risk factor values. Additionally, the authors recommend that future researchers identify and document strategies for mitigation of safety risk of constructing the design features. The author also suggests a study focusing on the risk of hazards (struck by object, fall on same level) while constructing each design feature. Finally, it is suggested that future researchers quantify the construction safety risks (increase or decrease) as a result of interaction among building construction activities.

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