Effect of Safety and Environmental Variables on Task Durations in Steel Erection

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Abstract: In spite of the efforts by government agencies, labor organizations, and researchers in the field of health and safety, injuries and fatalities continue to affect the construction industry. In 2002 the construction industry had the undesirable distinction of having two of the most dangerous occupations in the United States, with fatalities among structural steel workers at 58.2 per 100,000 workers (fourth highest rate) and among construction laborers at 27.7 per 100,000 workers (ninth highest rate). Costs associated with construction accidents, such as increased insurance premiums and medical expenses, and loss of productivity are also concerns in the industry. It has not been demonstrated how unsafe working conditions affect worker performance, and the impact of unsafe work practices on worker performance has not been quantified. This paper describes a methodology that included direct observation of steel erection activities and statistical analysis of task duration data. The data collected at steel erection sites included safety conditions such as the use of personal protective equipment (PPE), elevation of the work area, environmental conditions such as temperature and humidity, and worker performance in the form of task durations. Analysis of variance (ANOVA) analysis of 186 of steel erection task durations collected over a six-month period showed that the use of personal protective equipment (PPE), the time of day during which the operation was being performed, the elevation at which the work was being performed, and the presence of decking below the work area had statistically significant effects on the durations of steel erection tasks.

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Introduction

Of the 1,121 workplace fatalities in 2002, approximately 20% of them occurred in construction-related accidents (BLS 2002). Structural steel workers ranked fourth and construction laborers ranked ninth among the most dangerous occupations, with 58.2 and 27.7 fatalities per 100,000 workers, respectively, (BLS 2002). About 33% of all fatalities in the construction industry are related to falls (BLS 2002). In steel erection, 63% of fatalities are the result of falls. Present statistics show that injuries and fatalities are significant problems that continue to affect the steel erection industry.

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Past and current research in construction safety has focused on analysis of accident statistics to identify the main causes of accidents and injuries (Fullman 1984; Goldsmith 1987; Culvert et al. 1990, 1992; Davies and Tomasin 1990; La Bette 1990; MacCollum 1990; Rietze 1990; Helander 1991; Peyton and Rubio 1991; Hinze 1997). Also, Hinze (1997), Abdelhamid and Everett (2000), Toole (2002a,b), and others have developed models that relate construction accidents and injuries to worker behavior. Once the causes of accidents are understood, steps are taken to avoid hazards and unsafe behavior that leads to accidents. Some of these measures include safety policies, safety committees, safety training, and safety meetings (Hoonakker et al. 2003). Personal protective equipment (PPE) is a last line of defense against the unavoidable hazards faced by workers. In steel erection, one of the most often used types of PPE is fall protection, which is designed to protect workers by preventing impact with a lower level after a fall occurs.

To provide comfortable equipment, the design of PPE takes into consideration the anthropometric characteristics of workers. However, many workers say that this equipment, which is meant to protect them, sometimes hinders their movement and slows them down. This perception is of concern because it indicates a reason workers do not always make appropriate use of the PPE provided. This issue must be addressed to increase adherence to safety procedures, including appropriate PPE use.

Not using the required PPE or following safety procedures is a known cause of injuries and fatalities in construction (Huang and Hinze 2003). A fatality or injury at the job site can cause an estimated decrease in productivity of up to 33% within the first 48 h following the accident (Coble et al. 2000). This decrease in productivity is the result of work stopped while the accident is

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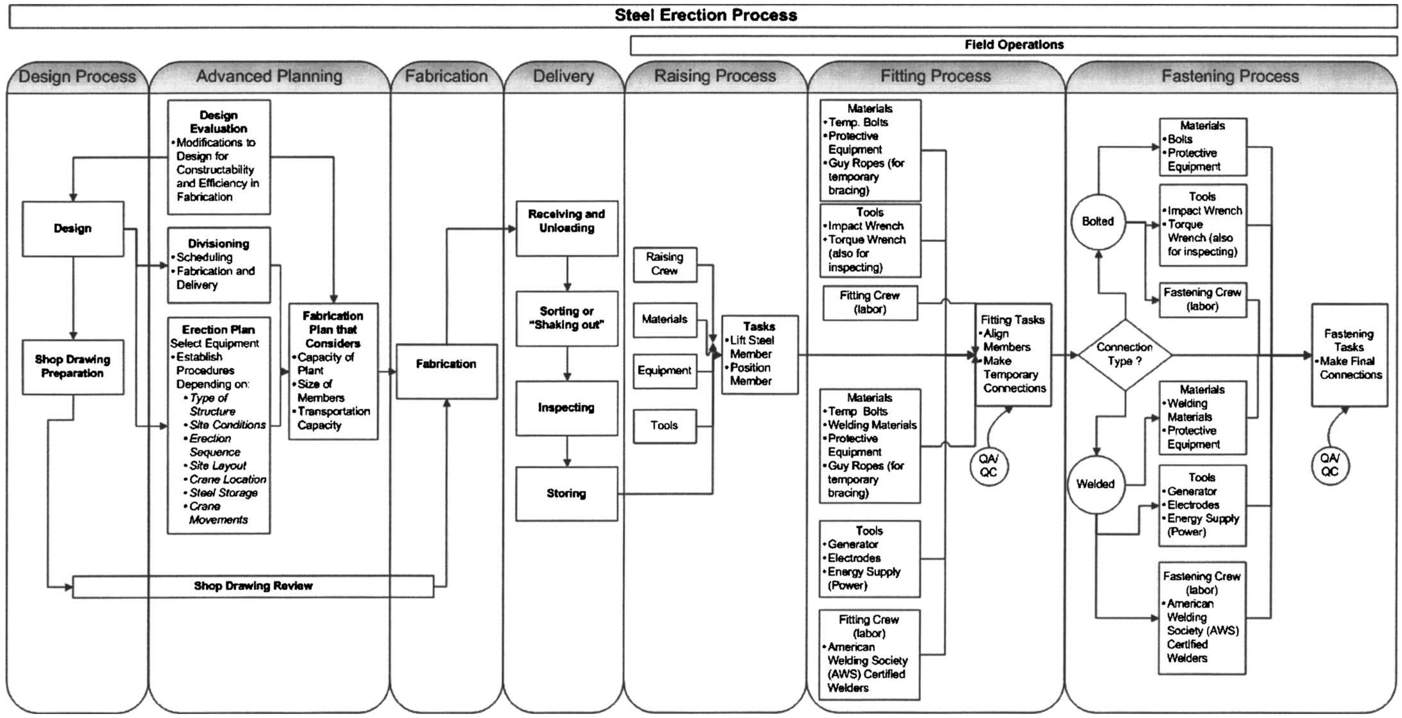

Fig. 1. Steel erection process model

investigated and of the diversion of workers' attention in the vicinity of the accident. One strategy to reduce the impact of accidents on the productivity of construction processes is to increase the use of required PPE, but to increase adherence to safety procedures that call for the use of provided PPE, the effect of PPE on the performance of workers needs to be quantified. Quantification of this impact can be accomplished by evaluating the performance time of workers on tasks that require the use of PPE.

This paper explores the effects of the use of PPE and the environmental conditions on task durations in steel erection. Task duration data, as well as data related to safety conditions in steel erection, were analyzed to determine the effects of the use of PPE and the environmental variables on the duration of the tasks observed. The results are expected to be valuable to the industry, demonstrating that adherence to safety procedures results in minimal loss of performance, thereby motivating workers to use the required safety equipment. The specific tasks considered in the analysis will be described in subsequent sections. Since this study was observational in nature, direct interaction with the workers was not possible. Therefore, this paper does not consider the effects of variables related to the personal characteristics of the ironworkers, including work experience, safety training, age, and health conditions. This limitation can be addressed in future studies where observations can be made in controlled environments and data on the workers' characteristics is available.

The following sections are intended to provide some background information about the steel erection process.

Review of Safety and Productivity in the Steel Erection Process

The Steel Erection Process

Steel erection consists of the placement and installation of iron or steel girders, columns, and other structures. Ironworkers unload and stack the prefabricated steel and then hoist the steel by attaching cables (slings) to the steel and to a crane or derrick. Fig. 1 shows a model of the steel erection process that was developed from information obtained during the preliminary data collection phase of the study. This paper considers the field operations component of the model. Three main activities are involved in the field operations component: *raising*, *fitting*, and *fastening*. A description of these activities is provided in Table 1. This paper focuses on safety issues related to the first two activities (raising and fitting), which can be considered the initial stages of the steel erection process. The decking of the structure is an activity that occurs after fastening and in concert with the raising and fitting activities.

The tasks involved in the raising and fitting activities of the steel erection process are described in Table 2. During the preliminary data collection phase of the study, several steel erection

Table 1. Steel Erection Activities

Activity	Description
Raising	In the raising activity, the structural steel elements are lifted to the installation point and then positioned in preparation for the initial connections.
Fitting	This activity entails the initial connection of the structural steel members. In this stage not all the bolts required at the connection points are installed and the ones installed are tightened with a hand wrench. OSHA's regulations state that two bolts are to be used at this stage of the process for steel beams and all required bolts, for steel columns (OSHA Code Subpart R, Steel Erection, Section 1926.760).
Fastening	At this stage the final connections are made. The remaining bolts required at all connection points are installed and, together with the bolts previously installed, tightened as per specifications using an impact wrench.

Note: OSHA=Occupational Safety and Health Administration.

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Table 2. Steel Erection Tasks

Task	Description
1–Rigging	The riggers grab the hoisting cable; this task ends when the load is released by the rigger.
2–Hoisting	The load starts to be hoisted; this task ends when the connector grabs the load to begin the positioning of the load in preparation for connection.
3–Position	The connector grabs the load for positioning; this task ends when either of the two connectors inserts the reamer or spud bar into one of the bolt holes.
4–Connect	This task starts when either one of the two connectors inserts the reamer or spud bar into one of the bolt holes; this task ends when the last connector finishes placing the last required bolt. The worker is considered a "connector" only when working with "hoisting equipment," which includes placing components as they are received from the hoisting equipment and then connecting those components while the hoisting equipment is overhead.
5–Unhook	One of the two connectors instructs the crane operator to lower the hoisting cable to allow the worker to unhook it, and the crane begins to return for the element.
6–Return	The crane starts to return from placing the element; this task ends when the rigger grabs the hoisting cable.

sites were visited and practitioners in steel erection were interviewed. A detailed description of the data collection process is provided in subsequent sections of this paper. From the data collected during the study the tasks that involved direct work by labor and that are performed on elevated surfaces compose 55% of the time required for the installation of steel beams. The remaining 45% of the time required involves the use of the crane and a reduced amount of labor at ground level. Fig. 2 shows the distribution per task of the time required to install one steel beam.

The *position*, *connect*, and *unhook* tasks were selected for the analysis because workers are more likely to fall from high elevations while performing these tasks. A study by Slaughter and Eraso (1997) evaluated the impact of innovations on construction processes considering the level of danger posed by the tasks. Based on the standard causes of construction injuries, Slaughter and Eraso developed a danger index for selected steel erection tasks, which was weighted by the number of structural steel members installed and the time the workers were exposed to different hazards. An important component of the danger index is falls, one of the three main causes of injuries when performing the position, connect, and unhook tasks.

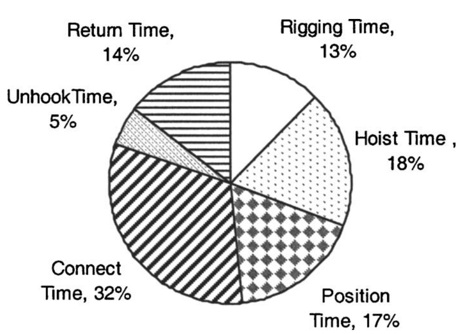

Fig. 2. Steel erection task duration distribution

Steel erection work is usually performed in all kinds of weather, but work performed at great heights may be suspended during wet, icy, or extremely windy conditions. Because of the high risk of falls encountered in steel erections, workers use safety devices such as fall arrest systems, safety harnesses, and nets.

Organizations such as the American Society of Civil Engineers (ASCE), the Associated General Contractors of America (AGC), the American Institute of Architects (AIA), the Occupational Safety and Health Administration (OSHA), and the American National Standards Institute (ANSI) have developed contract documents and standards addressing safety issues on construction sites. Toole (2002a) compared several existing contract documents and safety standards and found that there are significant differences in the site safety standards for each entity involved in the construction process. The safety standards that most directly address safety issues in steel erection are the OSHA steel erection standard (Subpart R, Steel Erection) and the "Construction and Demolition Operations—Steel Erection—Safety Requirements (ANSI A.10.13)" by the American National Standards Institute (ANSI). The purpose of these standards is to prevent the increasing number of injuries and fatalities that result from hazards in the steel erection process, including falls from elevations. Because the OSHA standards are the most widely accepted in the construction industry, only this standard will be discussed in this paper.

The Occupational Safety and Health Administration Steel Erection Standard

The first steel erection standard (Subpart R, Steel Erection) was part of the Occupational Safety and Health Act (known as "the Act" in the industry) enacted by Congress in 1970. The standard was adopted in 1971 when the Safety and Health Regulations for Construction were redesignated as part 1926 of the Code of Federal Regulations (CFR). The original steel erection standard included requirements for flooring, steel assembly, bolting, plumbing up, and related operations. In addition, the means and methods for fall protection in steel erection were covered by Subpart E, Personal Protective and Life Saving Equipment. The first revision to the steel erection standard was made in 1974 when the temporary flooring requirement was revised pursuant to a rule making conducted under section 6(b) of the Act (39 FR 24361). After several requests for revisions to the steel erection standard, in 1991 OSHA published a Federal Register notice of intent to establish a negotiated rule-making committee (57 FR 61860), but the revision process did not end until nine years later on June 12, 2000, when the rule-making record was certified. Some of the major changes made to Subpart R, Steel Erection are related to fall protection requirements, the duties of the controlling contractors, the site layout, planning of steel erection activities, specific requirements for hoisting and rigging activities, design requirements for anchor bolts, and design requirements for double connection (U.S. Department of Labor 2001). In addition to the changes to Subpart R, Steel Erection, there were revisions to Subpart M, Fall Protection, for purposes of consistency. Prior to the revisions to the standard in 2000, Subpart M stated that the requirements related to fall protection in steel erection were provided in Section 1926.105 and in Subpart R. The revised standard changed Subpart M to include fall protection requirements for construction of towers and tanks only. This revision made clear that steel erection is covered exclusively by Subpart R.

The effectiveness of the new OSHA steel erection standard, which became effective on July 18, 2002, is still not known. The

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Table 3. Data Collected at Steel Erection Sites

Project	Dates of data collection	Type of data collected
Valparaiso University Library	January 2003	Hazard assessment
Entrepreneurship Center Building at Purdue University	March 2003	Hazard assessment
Chemical Engineering Building Expansion at Purdue University	April–May 2003	Task duration data Evironmental conditions Safety-related conditions
Stadium Avenue Dining Hall at Purdue University	May–July 2003	Task duration data Environmental conditions Safety-related conditions
West Lafayette Public Library	August 2003	Hazard assessment
Birck Nanotechnology Research Center at Purdue University	September–October 2003	Task duration data Environmental conditions Safety-related conditions
Presyterian Church Building in West Lafayette, Indiana	February 2004	Hazard assessment

new standard is one of the first OSHA standards developed under the Negotiated Rule-making Act of 1990 and the Department of Labor's negotiated rule-making policy. The new steel erection standard places special emphasis on the most serious hazards that workers encounter during the steel erection process, including falling loads, mishandled decking, unstable columns, double connections, mishandled steel joints, and falls to lower levels. OSHA estimates that the new steel erection standard will save the steel erection industry approximately $40 million a year in costs associated with lost-workday injuries such as lost productivity, medical expenses, and insurance costs (Meilinger 2001). The aspects of this standard related to the hazard of falls from elevations must be considered to understand their impact on the performance of steel erection workers.

Productivity and Safety Issues in Steel Erection

The American Institute of Steel Construction (AISC) has identified productivity as an important issue affecting the steel construction industry. According to the AISC, a 25% reduction in the time required to erect a steel structure is needed to maintain competitiveness (Lytle et al. 2002). Reducing fabrication and erection time and increasing worker safety are issues that must be addressed for the industry to remain competitive.

Productivity of the steel erection process is affected by a number of factors, including the type of equipment used, fabrication and delivery of material, and labor resources. Because labor is a key component of construction processes, labor performance can be used as an indicator of process productivity. For example, in the initial stage of the steel erection process, four out of the six tasks required for the installation of structural members—*rigging, position, connect*, and *unhook*—are dependent mainly on work performed by ironworkers. The time taken by an ironworker to perform these initial tasks can be used as a measure of labor performance.

Research Methodology

Field observation of phenomena in their natural state is a valuable tool for understanding the effects of variables inherent to construction processes. To determine the effect of the selected variables on the performance of ironworkers, site visits were conducted at several steel erection projects in the state of Indiana between January 2003 and February 2004. Data collected at each site on the safety-related aspects of the steel erection process and worker performance is presented in Table 3.

The direct observation method was used in this study, allowing the researcher to "be part of the group without being observed or obtrusive" (Trochim 2001). The benefits of the direct observation method include minimization of the influence of the observer on the behavior of the subjects and more flexibility, that is, the study need not be structured around a hypothesis. Findings from observational research are considered strong in validity because the researcher can collect substantial information about different aspects of the behavior of interest (Trochim 2001). Information collected using the observational method can include the environmental factors that might influence the subjects' behavior, such as motion, and the actions specific to the subjects being observed, such as interactions with tools and materials. The drawbacks of this method include the inability of the researcher to control the variables being observed, problems with reliability (the extent to which the observations can be replicated) and external validity (the extent to which the findings can be extended to other groups), and the observer's subjectivity.

A total of 186 observations related to worker performance (task duration) were collected at three of the projects visited, which were located at the Purdue University campus in West Lafayette, Ind. The data were collected on different days at various periods during typical 8-h workdays between April and October 2003. During each visit one or two observers recorded the data. When there were two observers, one would operate the video equipment, take still photographs, and collect data related to safety conditions while the second observer recorded task duration data using a stopwatch. In addition to duration data, environmental conditions at the job site, crew size information, and the location of the workers during the process were also recorded. Any delays observed, such as nonproductive time, delays in material delivery, and difficulty in installation of elements, were also recorded. When there was only one observer, the task duration data was retrieved from the recorded videos. The characteristics of each project were important because they provided a representative sample of possible working conditions, that is, different elevations, inclined surfaces, and different installation configurations of steel members. The types of projects where the data used for analysis were collected are shown in Table 4.

Data on project characteristics related to safety management were also collected. The most important items observed were the presence of safety personnel, the size of the steel erection company, and the size of the general contracting company. Collecting this data allowed for aggregation of the observations since a variable that considered the characteristics of the projects was included in the analysis of the data. A summary of project characteristics is presented in Table 5.

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Table 4. Projects Used for Data Analysis

Project description	Dates of data collection	Number of observations
Project 1—8,919 m^2 (96,000 ft^2), five-story addition to existing academic building	April–May 2003	62
Project 2—two-story dining hall	May–July 2003	71
Project 3—17,373 m^2 (187,000 ft^2) three-story research facility	September–October 2003	53
Total		186

One limitation of the data collection process was that observations could not be made for all the variables studied. In observational studies the researcher has no control over the process being investigated. This limitation is significant in studies of safety issues because the researcher cannot control the safety behavior of the workers; for example, he cannot ask the workers to forego safety regulations.

Construction workers' behavior regarding safety may be influenced by what they perceive as safe or unsafe. Based on their personal perception, they make decisions on when they choose to follow or not follow the required safety precautions. Huang and Hinze (2003) found that the level of appropriate use of PPE is not satisfactory. Enforcement of safety regulations by supervisors and the safety culture in the company are factors that motivate workers to use safety equipment more effectively. If the company promotes safety as one of its core values, it can be expected that the workers will be more motivated to make use of the safety equipment available.

Delays in material delivery and equipment breakdowns allowed only a limited number of observations to be collected on several days during the data collection period. Another factor that affected the number of observations obtained was weather. Extremely low temperatures (below 6.67°C) caused suspension of work, and on days after it had rained, work was suspended for safety concerns with wet surfaces.

Data Analysis

The data collected at the steel erection sites were analyzed to determine the effects of several factors (environmental and safety-related) on the performance of the ironworkers (task duration). The performance measure used was the duration of the tasks that the ironworkers performed. Analysis of variance (ANOVA) was used to determine if there were significant differences in the average duration of the tasks observed under different conditions related to the variables studied. The results of the data analysis are presented in the subsequent sections.

Analysis of Steel Erection Task Duration

Modeling the influence of environmental and safety conditions on performance involved using ANOVA to determine if there were significant differences between the average duration of the three steel erection tasks (namely, positioning, connecting, and unhooking) under the different safety and environmental conditions studied. The duration of the three selected steel erection tasks were designated as the response variables. The environmental and safety-related conditions observed were designated as the explanatory variables (sometimes referred to as factors or treatments). A description of the variables used in the analysis of the variation of task durations in steel erection is included in Table 6. The analysis of the data was performed using the general linear model (GLM) procedure in the SAS software (SAS Institute Inc.).

When the underlying assumptions of ANOVA were examined, it was observed that the normality and the constant variance of the residuals assumptions were violated. In cases where the ANOVA assumptions were violated, transformations of the response variable were used, which can stabilize the error variances and can bring the distribution of the error terms closer to a normal distribution. Three of the most common transformations that can be used to address the violation of ANOVA assumptions are the logarithmic, square root, and reciprocal transformations (Neter et al. 1996). The logarithmic transformation provided the best results for correcting the nonconstant variance problem and bringing the residuals closer to a normal distribution. Several outlying observations were identified, and after evaluating the studentized re-

Table 5. Project Characteristics Related to Safety Performance

	Characteristics		
Project	Safety management	General contractor (company size and safety program)	Steel erector (company size and safety program)
Project 1	• The project did not have a full time safety coordinator present at the job site.	• The general contractor was a medium-size company. • The general contractor had an established safety program. • The general contractor did not mandate that the subcontractor enforce his own safety regulation.	• The steel erection company was a medium-size company. • The company had an organized safety program.
Project 2	• No safety engineer or safety coordinator was present at the job site.	• The general contractor was a small-size company. • The general contractor did not have an organized safety program.	• The steel erector was a small company without an organized safety program.
Project 3	• A safety engineer or safety coordinator was present at the job site, and there were regular site visits by the company's safety director.	• The general contractor was a medium-size company. • The general contractor had an established safety program and strictly enforced it at the project.	• The steel erection company was a medium-size company with an organized safety program.

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Table 6. Variables Used in the Development of Models

Variable	Description
Position	Response variable measured as the duration of the position task (s)
Connect	Response variable measured as the duration of the connect task (s).
Unhook	Response variable measured as the duration of the unhook task (s).
Temperature (temp)	Explanatory variable. Temperature recorded at the job site during data collection. The unit of measure is °C. This is considered a quantitative variable.
Humidity (hum)	Explanatory variable. The percent relative humidity recorded at the job site during the data collection. This is considered a quantitative variable.
Elevation (elev)	Explanatory variable. Elevation in feet taken from ground level to the point of installation of the steel member. This is considered a quantitative variable.
Time of day (tod)	Explanatory variable or factor. Time of day when observations where made. The factor has two levels and the values are: (1) if the data was collected in the morning hours (8:00 a.m. to 12:00 noon) and (0) if the data was collected in the afternoon hours (1:00 p.m. to 4:00 p.m.). This is a qualitative variable.
Use of fall protection equipment (protused)	Explanatory variable or factor. This factor has two levels. If the workers used fall protection equipment, the value was (1) and if the workers were not using the equipment, the value was (0). This is considered a qualitative variable.
Presence of decking below (deck)	Explanatory variable or factor. This factor has two levels. If the level below the workers had metal deck already installed, the factor had a value of (1), and it had a value of (0) if the deck was not installed. This is considered a qualitative variable.
Compliance (comp)	Explanatory variable or factor. Based on the combination of the protused and deck variables, this variable determines if there was a case of compliance or noncompliance with the OSHA steel erection standard. If the observation was a case of compliance, the factor had a value of (1) and if there was noncompliance, a value of (0).
Project (proj)	Explanatory variable or factor. Used to distinguish the project from which the data was obtained. The purpose of this variable was to detect the possible effects of variables that cannot be easily measured, such as type of project, safety management practices, etc. This factor has three levels, one for each project. Values of (1), (2), and (3) were assigned to the levels.

Note: OSHA=Occupational Safety and Health Administration.

siduals, it was determined that three observations had to be removed: one for the position task, none for the connect task, and two for the unhook task. These observations corresponded to unusual situations observed during the steel erection process. For example, workers talking to each other, workers smoking, and installation of steel members that did not fit correctly and so required additional installation time. The significance of the factors and their interactions were evaluated for each of the tasks, and final models were selected. The nature of the study, which involved observing construction workers in an uncontrolled environment, caused the coefficient of multiple determination (R^2) for the models to be small (in this case, R^2 was 0.26 for the position task, 0.10 for the connect task, and 0.27 for the unhook task). Table 7 shows the variables included in each of the models of the selected steel erection tasks. The following sections discuss the results obtained for each of the models and include interpretation of the variables and their implications for the safety and the performance of workers in the steel erection process.

Effect of Safety and Environmental Variables on the Position Task

The analysis of the data of the position task showed that there are four significant main effects: project, $p<0.0001$, time of day, $p=0.0009$, protection used, $p=0.0012$, and deck present, $p=0.0009$ (see Table 8). A main effect indicates to what extent the

Table 7. Analysis of Variance of Selected Steel Erection Tasks

	Position			Connect			Unhook		
R^2		0.26			0.10			0.27	
Source	*df*	*F*	*p*	*df*	*F*	*p*	*df*	*F*	*p*
Compliance (α)		NS			NS			NIM	
Project (β)	2	14.42	<0.0001		NS			NIM	
Time of day (γ)	1	11.31	0.0009	1	11.19	0.0010		NS	
Elevation (δ)	1	3.75	0.0544	1	5.00	0.0266		NS	
Protection used (φ)	1	10.82	0.0012		NS		1	28.95	<0.0001
Deck present (υ)	1	11.43	0.0009		NS			NS	
Temperature (Ψ)		NS			NS			NS	
Humidity (ω)		NS			NS			NS	
PCL (combination of project and compliance) (ρ)		NIM			NIM		4	5.10	0.0007

Note: NS=not significant at $\alpha=0.05$; NIM=not included in model.

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Table 8. Parameter Estimates and Multiplicative Terms: Position Task Model

Factors/variables	Level value	Parameter estimates	Multiplicative terms
Task mean (μ)		1.71	5.53 s
Project (β)	$i=1$	−0.0390	0.9617
Project (β)	$i=2$	−0.1431	0.8666
Project (β)	$i=3$	0.1822	1.1998
Time of day (γ)	$j=0$	0	1
Time of day (γ)	$j=1$	0.1521	1.1643
Elevation (δ)		−0.0028	0.9971[a]
Protection used (φ)	$l=0$	0	1
Protection used (φ)	$l=1$	0.2936	1.3412
Deck present (υ)	$m=0$	0	1
Deck present (υ)	$m=1$	0.1885	1.2074

[a]To apply factor multiply by $e^{-0.0028\text{xelev}}=(0.9971)^{\text{elev}}$.

factor-level mean deviates from the overall mean (Neter et al. 1996). A significant main effect suggests that the mean of the response variable is significantly different from its overall mean at the different values of the factor being analyzed. For example, a significant main effect for the factor protection used indicates that the mean duration of the position task is significantly different when fall protection equipment is used and when it is not used. The elevation variable was close to being significant at the $\alpha=0.05$ level, $p=0.0544$ (see Table 7). Elevation was included in the model because it is considered to be an important variable related to the safety of the ironworker. The compliance factor and the temperature and humidity variables were not significant. There were no significant interactions among the factors analyzed in the model.

The Tukey–Kramer multiple comparison procedure was used to determine if there were significant differences between the levels of the factors analyzed. The analysis showed that the average duration of the position task was significantly higher in the morning hours, significantly higher when fall protection equipment was used, and significantly higher when decking was present under the floor being erected. The average task duration on project 1 was significantly lower than on project 3 ($p=0.0002$) but not significantly different from project 2 ($p=0.5521$). The average task duration on project 2 was significantly lower than on project 3 ($p=0.0008$). It can be inferred that characteristics related to safety management and project and company size could have an effect on task durations on projects similar to project 3, where task duration can be expected to be higher than on projects similar to projects 1 and 2. The main differences between projects 1, 2, and 3 are the presence of a full-time safety coordinator or manager on site and the size of the companies (steel erector and general contractor).

Eq. (1) shows the final model for the position task, which describes the effect of the safety-related variables and the environmental variables on the task duration. Because a logarithmic transformation was used in the modeling process, the model was transformed to obtain the correct units of the response variable. The resulting transformation is shown in Eq. (2).

$$\text{Log}(\text{Duration}_{\text{Position}}) = \mu + \beta_i + \gamma_j + \delta \times \text{elevation} + \phi_k + \upsilon_l + \varepsilon_{ijkl} \quad (1)$$

$$\text{Duration}_{\text{Position}} = e^{(\mu+\beta_i+\gamma_j+\delta\times\text{elevation}+\phi_k+\upsilon_l+\varepsilon_{ijkl})} \quad (2)$$

Table 9. Parameter Estimates and Multiplicative Terms: Connect Task Model

Factors/variables	Level value	Parameter estimates	Multiplicative terms
Task mean (μ)		1.9569	7.08 s
Time of day (γ)	$i=0$	0	1
Time of day (γ)	$i=1$	0.1638	1.1779
Elevation (δ)		0.0028	1.0028

Note: To apply factor multiply by $e^{0.0028\text{xelev}}=(1.0028)^{\text{elev}}$.

The resulting model represented by Eq. (2) is considered a multiplicative model. The average task duration (e^{μ}) is multiplied by each of the terms corresponding to the factors and variables in the model. Table 8 shows the parameter estimates and multiplicative terms corresponding to the levels of the factors and variables included in the model. As shown by the values of the multiplicative terms of the project factor, the position task duration is reduced relative to the mean on projects with characteristics similar to those of projects 1 and 2, by 3.8 and 13.3%, respectively. On projects with characteristics similar to those of project 3, the position task duration is increased by almost 20%, which can be attributed to the strict enforcement of safety regulations. For example, when workers make use of fall protection equipment, task duration tended to increase by approximately 34%. If decking is present in the floor below the workers performing the position task, the duration increased by approximately 21%. Elevation of the work area decreases task duration by a factor of 0.9971 raised to the elevation in feet. For example, a project with characteristics similar to project 3, in which the position task is performed in the morning hours at an elevation of 9.14 m (30 ft) and fall protection is used having decking below the work area, the task duration increased by 1.82 s.

Effect of Safety and Environmental Variables on the Connect Task

The factors that were found to have a significant effect on the duration of the connect task were time of day, $p=0.0010$, and elevation, $p=0.0266$. The compliance, project, protection used, and deck present factors and the temperature and humidity variables were not significant in this model. No significant interactions where observed among the factors analyzed.

The results of the Tukey–Kramer multiple comparison procedure showed that the mean duration of the connect task was significantly higher in the morning hours. Eq. (3) shows the final model for the connect task. The application of the logarithmic transformation of the data requires that the model be transformed to obtain the correct units of time. Eq. (4) shows the transformed model, which is also a multiplicative model. Table 9 shows the parameter estimates and the multiplicative terms for the factors in the model. Similar to the position task, the connect task duration was higher in the morning hours by approximately 18% (see Table 9). The results also showed that the connect task duration increased with increasing elevation by a factor of 1.0028 raised to the elevation in feet (see Table 9).

$$\text{Log}(\text{Duration}_{\text{Connect}}) = \mu + \gamma_i + \delta \times \text{elevation} + \varepsilon_i \quad (3)$$

$$\text{Duration}_{\text{Connect}} = e^{(\mu+\gamma_i+\delta\times\text{elevation}+\varepsilon_i)} \quad (4)$$

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Table 10. The PCL Factor

Factors		
Project	Compliance	PCL (levels)
Project 1	0=No	1
Project 1	1=Yes	2
Project 2	0=No	3
Project 2	1=Yes	4
Project 3	0=No	5
Project 3	1=Yes	Empty cell

Effect of Safety and Environmental Variables on the Unhook Task

The compliance and project factors were not included in the model since there were empty cells on some of the combinations of these factors. This caused some parameter estimates to be inestimable. To solve this, a new factor, PCL, was created as a combination of the project and compliance factors. The PCL factor made possible effects on the response apparent. In his study on the productivity in earth-moving operations, Smith (1999) used a similar approach to account for the differences between the projects studied. Table 10 shows the levels of the PCL factor. When this factor was included in the model, it was found to be significant ($\alpha=0.05$). There were two significant factors on the unhook task model: the PCL factor, $p=0.0007$, and the protection used factor, $p<0.0001$. The deck present factor and the temperature and humidity variables were not significant in this model. The only interaction observed during the model development process was between the temperature and humidity variables. This interaction was significant but not important; it was a mild interaction that was eliminated because it did not benefit the performance of the model in explaining the effects of the other factors and variables on the unhook task duration. It was included as a covariate to help explain variability in the data but was not successful. For this reason the final model did not include the temperature and humidity variables.

As with the previous two models, the application of the logarithmic transformation of the data requires a transformation of the model to obtain the correct units of time. Eq. (6) shows the transformed model. The unhook model is also a multiplicative model. The parameter estimates and the multiplicative terms for the factors in the unhook model are shown in Table 11.

$$\text{Log}(\text{Duration}_{\text{Unhook}}) = \mu + \rho_i + \varphi_j + \varepsilon_{ij} \qquad (5)$$

$$\text{Duration}_{\text{Unhook}} = e^{(\mu+\rho_i+\varphi_j+\varepsilon_{ij})} \qquad (6)$$

Table 11. Parameter Estimates and Multiplicative Terms: Unhock Test Model

Factors/variables	Level value	Parameter estimates	Multiplicative terms
Task mean (μ)		1.1287	3.09 s
PCL (ρ)	$i=1$	−0.0001	0.9999
PCL (ρ)	$i=2$	−0.0864	0.9172
PCL (ρ)	$i=3$	−0.1774	0.8374
PCL (ρ)	$i=4$	−0.0028	0.9972
PCL (ρ)	$i=5$	0.2668	1.3058
Protection used (φ)	$j=0$	0	1
Protection used (φ)	$j=1$	0.3756	1.4558

Table 12. Tukey–Kramer Multiple Comparison Results for PCL Factor

i/j	1	2	3	4	5
1		0.5905	0.2443	1.0000	0.0405
2	0.5905		0.8481	0.6561	0.0034
3	0.2443	0.8481		0.0610	0.0016
4	1.0000	0.6561	0.0610		0.0426
5	0.0405	0.0034	0.0016	0.0426	

The results of the Tukey–Kramer multiple comparison procedure showed that the mean unhook task duration was significantly higher (approximately 31%) for projects with characteristics similar to those of project 3, with no noncompliance of safety standards related to fall protection (PCL when $i=5$), than for projects with characteristics described by PCL on all other levels. There was no significant difference between the other levels of the PCL factor. The p-values of the Tukey–Kramer comparison procedure for the PCL factor are included in Table 12. The results for the protection used factor show that the unhook task duration is approximately 46% higher when fall protection equipment was used ($p<0.0001$).

It is important to understand the practical significance of the results obtained from the models developed. Since the tasks studied are of short duration (between three and seven seconds on average), the observed increase in task duration should not be interpreted as a reason for not using fall protection equipment. On the contrary, the results show that safety-related factors, such as the enforcement of safety regulations, have a relatively small effect on performance time. Therefore, compliance with safety regulations, such as the use of required fall protection equipment, is strongly encouraged.

Impact on Steel Beam Installation Time

The following example shows how the effects of the variables studied could impact the total installation cycle for one steel beam. It is assumed that only the duration of the position, connect, and unhook tasks are affected by the variables studied. It is also assumed that the average duration of the remaining tasks (rigging, hoisting, and return) for the total installation cycle of one steel beam are not affected by the variables studied. The average duration for these tasks was obtained from the data collected at the steel erection sites. The following conditions are considered in the example:

- Project is similar to project 3 (see Table 5 for characteristics).
- Steel erection is conducted in the morning.
- Elevation of the work area=9.14 m (30 ft).
- Fall protection is used.
- Decking is present on the floor below the work area.

After applying the values for the factors in Eqs. (2), (4), and (6), the total cycle time for the installation of a steel beam increased from 6.1 to 6.2 min, a net increase of 2% or 0.01 min. From Figs. 3 and 4 it can be observed that a marginal increase in total cycle time occurs when the selected conditions are considered.

Discussion and Conclusions

Traditionally safety has not been included as a primary factor in prior studies on labor performance. The objective of this paper was to evaluate how factors related to PPE and environmental

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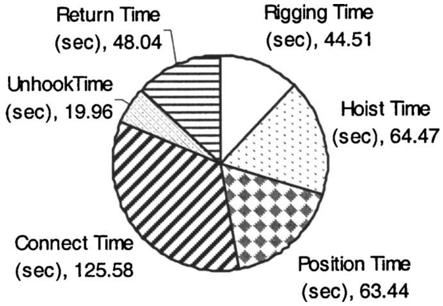

Fig. 3. Steel beam installation cycle—tasks unaffected

conditions in steel erection sites can affect the performance time of ironworkers (task duration). The methods used to accomplish the objectives included site observations at several steel erection projects and ANOVA modeling using 186 observations of task durations in steel erection. The results presented in this paper show that it is possible to quantify the impact of PPE and environmental conditions on ironworkers' performance by analyzing task duration data. By quantifying the effect that safety practices, in particular PPE, have on worker performance, modification to improve performance of construction processes could be evaluated considering the effects on worker safety. More extensive evaluation could be undertaken to develop safety equipment that assists workers instead of hindering their movement and, therefore, their performance. These efforts could assist the steel erection industry in achieving the AISC's goal to reduce installation time while improving the safety of ironworkers.

Workers were observed while performing steel erection tasks, and the hazard of falls from elevations was investigated to show the effects of environmental and safety conditions on worker performance in three key tasks: position, connect, and unhook. Four factors (project, time-of day, protection used, and deck present) significantly affected the position task duration while two factors (time of day and elevation) affected the connect task; and two factors (PCL and protection used) affected the unhook task.

It appears that tasks such as position, which require more movement from the worker, are influenced by many factors and that these factors can have a combined effect on the balance of ironworkers while moving, thus increasing task duration. For example, the use of fall protection significantly affected the duration of the position and unhook tasks, which was expected because these tasks involve more movement and because fall protection equipment appears to affect a worker's movement. Another safety-related variable that significantly affected the position task was the presence of decking below the workers. The analysis showed that the task duration was higher when decking was present on the floor below. This finding might at first appear contradictory because, when there is decking below the workers, they one would assume feel safer and, therefore, work at a faster rate. However, other conditions can influence the worker when there is decking below. For example, more intense activity may occur on the decked level, and this activity will be closer to the worker who is installing steel members. Therefore, worker perception of risk may increase, resulting in increased task duration. Additional factors that may influence worker performance when there is decking below should be considered in future studies.

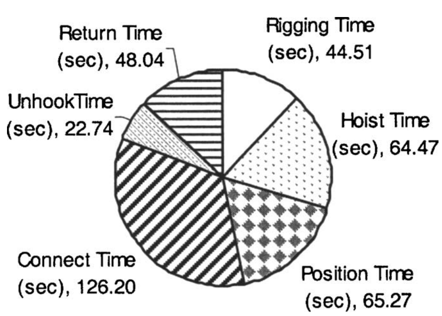

Fig. 4. Steel beam installation cycle—tasks affected

The time of day and elevation variables significantly affected only the position and connect tasks. Increasing the elevation actually decreased the average duration of the position tasks, perhaps because as the elevation of the structure increases, the structural members handled by the ironworker tend to be smaller making the degree of difficulty in handling those members less.

Another finding which seems to contradict expectations was the effect that the time of day variable had on the position and connect tasks. One might expect that during the afternoon hours fatigue and other factors would increase task duration. The analysis of the data collected in this study showed that task duration was actually longer in the morning hours. A possible explanation for this effect could be that it takes the worker some time to achieve a steady work rhythm, and therefore, the time to perform tasks in the morning is higher. Other variables related to the worker (age, experience, training, etc.) were not included in this study. Future studies should consider these variables to determine their contribution to variations in task durations in steel erection.

The perception on many construction sites is that the use of safety equipment increases the time required to perform specific tasks, and hence, many workers tend to neglect the use of safety equipment. To improve the use of PPE, the effectiveness of project managers in coordinating work to make efficient use of safety equipment should be evaluated. The possible increase in task duration resulting from the use of safety equipment could be offset by: (1) improved quality of equipment, (2) reduction in the occurrence of accidents, which results in cost savings from reduced insurance premiums, and (3) increased competitiveness in the industry due to a lower experience modifier rate (EMR).

Training, supervision, and coordination of workers can result in increased compliance, improved safety, and improved performance. The results presented in this paper describe the use of PPE as one factor that increases the time required to perform steel erection tasks. The observed impact must not be interpreted as a reason to forego the use of PPE, but rather as an opportunity for further improvement in existing equipment and work procedures. Workers would benefit from lighter tools, improved installation procedures, and personal protective equipment that does not hinder worker movement, especially when working at heights.

This study was limited by the low number of observations for each of the variables analyzed and the number of variables included in the analysis. This is typical in observational studies in which there is no control over the process being investigated. This limitation could be addressed in future research by designing controlled experiments in simulated environments.

Significance to Research and Practitioner Community

The findings of this study demonstrate that a quantitative approach using task durations is a viable alternative in analysis of the effect of safety and environmental factors on construction

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operations. The results also show that observational studies can be used in construction research to evaluate worker performance. The direct observation of workers on the job site provides first-hand knowledge of the difficulties encountered by workers during the performance of their tasks. It is possible to employ an experimental design methodology that makes use of simulated environments to evaluate new safety strategies, i.e., process, safety equipment, etc., and to gauge the impact of these strategies on worker performance. There may be opportunities for additional research in the development of safety strategies that do not hinder worker performance. The present study is of significance to practitioners in the area of steel erection because it shows that the effects of safety-related and environmental factors can increase the duration of the position, connect, and unhook tasks but that the impact of this increase on the total cycle time is minimal. Therefore, it is recommended that steel erection contractors encourage continued use of PPE. Management could also benefit from an integrated construction planning process that takes into consideration the impact that safety practices have on worker performance and could plan the work so that neither worker performance nor safety are negatively affected. Such strategies must include safety training that considers the impact of PPE on worker performance.

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References

Abdelhamid, T. S., and Everett, J. G. (2000). "Identifying root causes of construction accidents." *J. Constr. Eng. Manage.*, 126(1), 52–60.

Bureau of Labor Statistics (BLS). (2002). *National census of fatal occupational injuries in 2001*, U.S. Department of Labor, Washington, D.C.

Coble, R. J., Hinze, J., and Haupt, T. C. (2000). *Construction safety and health management*, Prentice Hall, Englewood Cliffs, N.J.

Culvert, C., Florczak, G., Castell, R., Jr., Pelton, G., and Connolly, C. (1990). "Analysis of construction fatalities—The OSHA data 1985–1988." *Rep.*, Occupational Safety and Health Administration, U.S. Department of Labor, Washington, D.C.

Culvert, C., Marshall, M., and Connolly, C. (1992). "Construction accidents: The workers compensation data base, 1985–1988." *Rep.*, Occupational Safety and Health Administration, U.S. Department of Labor, Washington, D.C.

Davies, V. J., and Tomasin, K. (1990). *Construction safety handbook*. Thomas Telford, London.

Fullman, J. B. (1984). *Construction safety, security, and loss prevention*. Wiley, New York.

Goldsmith, D. (1987). *Safety management in construction and industry*. McGraw-Hill, New York.

Helander, M. G. (1991). "Safety hazards and motivation for safe work in the construction industry." *Int. J. Ind. Ergonom.*, 8(4), 205–223.

Hinze, J. W. (1997). *Construction safety*, Prentice Hall, Englewood Cliffs, N.J.

Hoonakker, P. L. T., Loushine, T., Kallman, J., Carayon, P., Kapp, A., and Smith, M. J. (2003). "Accidents, injuries, workers' compensation, safety and safety policy in construction industry: The effort/results paradox." *Int. Ergonomics Association (IEA) Conf.*, Seoul, Korea.

Huang, X., and Hinze, J. (2003). "Analysis of construction worker fall accidents." *J. Constr. Eng. Manage.*, 129(3), 262–271.

La Bete, C. R. (1990). "Innovative procedures in construction safety." *Professional Safety*, 35(4), 35–39.

Lytle, A. M., Saidi, K. S., Stone, W. C., and Gross, J. L. (2002). "Report of the National Institute of Standards and Technology (NIST) on Automated Steel Construction." *Proc., Int. Symp. on Automation and Robotics in Construction, 19th (ISARC)*, National Institute of Standards and Technology, Gaithersburg, Md, 247–253.

MacCollum, D. V. (1990). "Time for change in construction safety." *Professional Safety*, 35(2), 17–20.

Meilinger, F. (2001). "Protecting ironworkers." *Job Safety and Health Quarterly*, 13(1), 26–28.

Neter, J., et al. (1996). *Applied linear statistical models*, 4th Ed., McGraw-Hill, Burr Ridge, Ill.

Peyton, R. X., and Rubio, T. C. (1991). *Construction safety practices and principles*, Van Nostrand-Reinhold, New York.

Rietze, R. B. (1990). "Proactive construction management." *Professional Safety*, 35(1), 14–16.

SAS Institute Inc., *SAS version 8 user reference manual*, Cary, N.C.

Slaughter, E. S., and Eraso, M. (1997). "Simulation of structural steel erection to assess innovations." *IEEE Trans. Eng. Manage.*, 44(2), 196–207.

Smith, S. D. (1999). "Earthmoving productivity estimation using linear regression techniques." *J. Constr. Eng. Manage.*, 125(3), 133–141.

Toole, T. M. (2002a). "Comparison of site safety policies of construction industry trade groups." *Pract. Period. Struct. Des. Constr.*, 7(2), 90–95.

Toole, T. M. (2002b). "Construction site safety roles." *J. Constr. Eng. Manage.*, 128(3), 203–210.

Trochim, W. M. K. (2001). *The research methods knowledge base*, Atomic Dog, Cincinnati, Ohio.

U.S. Department of Labor. (2001). "Occupational safety and health standards for the construction industry." *29 CFR 1926* Occupational Safety and Health Administration, U.S. Government Printing Office, Washington, D.C.

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