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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 fatalities per 100,000 workers (4th highest rate) and construction laborers experiencing fatalities at the rate of 27.7 fatalities per 100,000 workers (9th highest rate) (Bureau of Labor Statistics, 2002).

In addition to the costs associated with construction accidents such as increased insurance premiums and medical expenses, loss of productivity is a cause for concern to the industry. For example, when a worker is injured, his/her productivity can decrease by 33% during the first 48 hours following the occurrence of the injury (Coble et al. 2000). It has not been proven how unsafe working conditions affect worker productivity, and the impact of unsafe work practices on worker performance has not been quantified. Many workers in the construction industry

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perceive that the use of safety enhancing devices adversely affects their productivity, and hence they tend to forgo the use of the safety equipment provided.

This paper presents the results from the analysis of observations at seven steel erection projects in Indiana and statistical analysis of one hundred and eighty six observations of task durations in steel erection collected over a six month period. The results of the analysis showed that task durations averaged 1.3 times longer when fall protection equipment was used and 1.2 times longer with decking installed on the level below the workers. In addition, task duration averaged 1.2 times longer in the morning hours than in the afternoon hours. These findings demonstrate that safety and environmental factors influence worker productivity and demonstrate the need for research in order to find the causes of these factors. Possible avenues for additional research include the development of improved Personal Protective Equipment (PPE), and exploring innovative means and methods of construction that improve productivity without adversely affecting the safety of the worker.

KEY WORDS

Steel erection, construction safety, fall protection, Personal Protective Equipment (PPE), ironworkers, task duration, falls from elevations

INTRODUCTION

Of all workplace fatalities in 2002, one thousand one hundred and twenty one (1,121), approximately 20%, occurred in construction related accidents (BLS 2002). Structural steel workers ranked fourth and construction laborers ranked ninth 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 the fatalities are the result of falls. When fatalities or injuries occur, the productivity of the construction worker is affected. A decrease in productivity of 33% can be observed within the first 48 hours following the occurrence of an injury (Coble et al. 2000). Not only is the productivity of the injured worker affected. Workers in the vicinity of the accident are also affected since the accident diverts their attention away from their work.

Continuous improvement in work practices is needed to reduce the incidence of falls in steel erection. This can be achieved by analyzing the impact of safety practices on worker performance in order to develop measures that enhance safety without reducing productivity.

Safety and productivity

Contractors tend to overlook the use of safety devices since they believe, without evidence, that the use of safety devices increases the time taken by the workers to perform their tasks, which in turn "impedes their productivity." Some contractors have pointed out that "the same safety standards that are intended to require the use of safety devices allows them to forgo the use of such devices in specific situations," and that sometimes they plan their work to take advantage of those “loopholes” in the safety standards. For instance, according to Section 1926.754 (b)(3) of the Occupational Safety and Health Administration (OSHA) Code Subpart R-Steel Erection, "a fully planked or decked floor or nets shall be maintained within two stories or 9.14m (30ft) directly under the area where steel erection is being performed". When connectors and workers who are deckers in a Controlled Decking Zone (CDZ) are at an elevation of 4.57m (15ft) to 9.14m (30ft) and there is decking installed on the floor below, they are required to wear fall protection equipment but not required to “tie off”. According to this rule, a worker who is

30.48m (100 ft) above the ground but less than 4.57m (15ft) to 9.14m (30ft) above the level below would not be required to use the fall protection equipment (i.e. "tie off") if there is decking at the level below. It is important then to determine if there are benefits to the performance of the worker when using protective equipment and to communicate those benefits so that workers will make more extensive use of the established safety requirements.

The American Institute of Steel Construction (AISC) has identified productivity as 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 the safety of the workers are issues that must be addressed for the industry to remain competitive.

Characteristics of steel erection work

Steel erection work involves three main activities: *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 as the initial stage 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.

Insert Table 1

The tasks involved in the *raising* and *fitting* activities of the steel erection process are described in Table 2. The *Position*, *Connect*, and *Unhook* tasks were selected for the analysis due to the high exposure to the hazard of falls from elevations that workers encounter 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, they developed a danger index for selected steel erection tasks. The index 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, since it is falls constitute one of the three main causes of injuries when performing the tasks of *Position*, *Connect* and *Unhook*. Being struck by objects or equipment, and getting caught in or between materials or equipment are some of the other causes of injuries and fatalities in steel erection.

Insert Table 2

This paper identifies hazards present in steel erection using the characteristics of: (1) the tools used, (2) the materials used, (3) the design of the structures, and (4) the process used. In addition, the influence of safety and environmental factors on task durations is evaluated.

FIELD OBSERVATION OF THE STEEL ERECTION PROCESS

Field observation of phenomena in their natural state is a valuable tool for understanding the effects of variables inherent to construction processes. 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). Benefits of the direct observation method include: minimization of the influence of the observer on the behavior of the subjects, and observations are usually flexible (not required to be structured around a hypothesis). Findings from observational research are considered strong in validity because the researcher is able to collect substantial information about different aspects of the behavior of interest (Trochim 2001). Information that can be collected using the observational method include: environmental factors that might influence subject behavior, and actions specific to the subjects being observed such as motion and interactions with tools and materials. Drawbacks of this method include the inability of the researcher to control the variables being observed, problems with reliability (the extent to replicate observations), generalizability or external validity (the extent to which the findings would be extended to other groups), and the subjective interpretation of the observer.

Safety and worker performance data collection at steel erection sites

Site visits were conducted at seven (7) steel erection projects in Indiana between the months of January 2003 and February 2004 to collect data related to safety aspects of the steel erection process and data related to worker performance. Table 3 shows the projects visited and the data collected at each. Various hazards associated with the different tasks were identified in terms of the materials used in the process (structural elements, bolts, tools, etc.), the tools used by the workers (hand tools, Personal Protective Equipment (PPE), machinery, etc.), the design of the structures (shape of structural members, configuration of members when installed, etc.), and the process of erecting the structure (interactions between workers and equipment, movements required, etc.).

Insert Table 3

One hundred and eighty six (186) observations related to worker performance (task duration) were collected at three projects. The three projects were located at the Purdue University campus in West Lafayette, Indiana. The data were collected on different days at various periods during typical 8-hour workdays between the months of April and October 2003. The characteristics of each project were important because they provided a representative sample of possible working conditions such as different elevations, inclined surfaces, and different installation configurations of steel members. Each task was measured using a stopwatch. In addition, video cameras and still photography recorded safety conditions during the data collection period. In addition to duration data, the environmental conditions at the job site, the crew size information and location of the workers during the process, were also recorded. The types of projects used in the data collection are shown in Table 4.

Insert Table 4

Data on project characteristics related to safety management was also collected. The most important items were the presence of safety personnel, size of the steel erection company, and size of the general contracting company. A summary of project characteristics is presented in Table 5.

Insert Table 5

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 of significance in studies of safety issues since the researcher cannot control the safety behavior of the workers, for example, by asking them not to follow safety regulations.

The behavior of construction workers regarding safety may be influenced by what they perceive as safe or unsafe. Based on this perception they make decisions on when 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 part of their core values of work ethic, 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 were another limitation during the data collection process. These events resulted in a limited number of observations to be collected on several days during the data collection period. Weather was another factor that affected the number of observations obtained. Extremely low temperatures (below 20 degrees Fahrenheit) caused suspension of the work. On days after it had rained, the work was also suspended for safety concerns with wet surfaces.

ANALYSIS OF THE DATA COLLECTED AT STEEL ERECTION SITES

The data collected at the steel erection sites were analyzed to identify hazards in steel erection tasks and to determine the effect of several factors (environment and safety related) on the performance of the ironworkers (task duration). The visual information obtained from video recordings and still photography, and the characteristics of the projects visited (design and management related) helped identify the hazards encountered by the ironworkers while performing steel erection tasks. Design related characteristics include the configuration of the structure (inclined surfaces, shape and size of elements, etc.), and number of stories. Management related characteristics include project coordination, safety management, and compliance with safety regulations among others. The measure of performance used was the duration of the tasks that the ironworkers performed. Analysis of Variance (ANOVA) was used to analyze the task duration data collected. The results of the analysis of the data are presented in the subsequent sections.

Identified hazards associated with steel erection tasks

Hsiao and Simeonov (2001) described three factors – environmental, task related and personal factors - that affect balance during roofing work, another activity that is performed at different elevations. Similarities between roofing work and steel erection, for instance: working at heights, handling heavy loads and tools, and walking on irregular surfaces, deems the use of these factors appropriate for the analysis of the steel erection process. Environmental factors concern the information available from visual and physical interactions. In steel erection, the elevation of the work area and the surfaces on which the ironworkers move are factors that can affect their balance and thus their performance. Task related factors include load handling, physical exertion and fatigue, and complexity of the tasks. The arduous nature of steel erection work makes task related factors important to the analysis of worker performance. Personal factors include individual differences, work experience, and interaction with personal protective equipment (PPE). The use of PPE is an important issue in steel erection since is the first line of defense for ironworkers, protecting them from the hazard of falls. The factors discusses can be used to identify possible health and safety issues and hazards in the performance of steel erection tasks

(Figure 1). Visual information about the tasks performed by steel erection workers (videos and still photographs) and the applicable safety standards were used during the identification of hazards present in the process.

Insert Figure 1

An example of the health and safety issues affecting ironworkers is the weight of the tools the worker must carry. A typical ironworker usually carries one or more wrenches, a crowbar or reamer, a bag of bolts and a safety harness. The combined weight of these items is approximately 22.7 kilograms (50 pounds). Figure 2 shows some of the hazards identified according to the selected criteria.

Many of the hazards observed at the job sites can be directly related to falls from elevations. The conditions related to this hazard must be considered to understand their impact on the performance of ironworkers. Using the OSHA steel erection standard (OSHA Code Subpart R - Steel Erection, Section 1926.760) three important conditions related to the hazard of falls from elevations were identified (see Table 6). The first (use of fall protection is required) and third (presence of decking on the level below the work level) conditions are important because their combination may dictate what safety precautions are required during the steel erection process. Some steel erection contractors may use this combination when planning the erection sequence to reduce the exposure of the worker to the risk of falling to lower levels. Other contractors may use the combination to prevent the loss of productivity that may be incurred when safety devices such as personal protective equipment (PPE) are used.

Insert Table 6

Table 7 lists the most common combinations of the three conditions related to the hazard of falls from elevations in steel erection. Workers performing steel section tasks under the conditions described by Cases 1 through 5 comply with OSHA safety standards while workers performing the same tasks under the conditions described by Case 6 do not comply with OSHA safety standards.

Insert Figure 2

Insert Table 7

Analysis of 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 conditions observed and the safety related conditions 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 8. The analysis of the data was performed using the general linear model (GLM) procedure in the SAS software (SAS Institute Inc., Cary, NC).

Insert Table 8

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 are violated, transformations of the response variable can be used to stabilize the error variances and usually 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 correcting the non constant variance problem and bringing the residuals closer to a normal distribution. Several outlying observations were identified and after evaluating the studentized residuals it was determined that very few observations had to be removed (one (1) for the *Position* Task, none for the *Connect* Task, and two (2) 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 required additional installation time. The significance of the factors and their interactions were evaluated for each of the tasks and final models were selected. Due to the nature of the study, which involved observing construction workers in an uncontrolled environment, the coefficient of multiple determination (R^2) for the models can be expected 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 9 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

(*Position, Connect,* and *Unhook*) and include interpretation of the variables and their implications for the safety and the performance of workers in the steel erection process.

Table 9

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 9). A main effect indicates to what extent the factor level means 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 or not used. The variable *Elevation* was close to being significant at the α=0.05 level, p = 0.0544 (see Table 9). Since *Elevation* is considered to be an important variable related to the safety of the ironworker it was decided to include it in the model. The factor *Compliance* and the variables *Temperature* and *Humidity* 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. It can be observed that the average task duration on Project

1 is 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 is significantly lower that 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).

Equation 2 shows the final model for the *Position* task. The purpose of the models is to describe the effect of the safety related variables and the environmental variables on the duration of the tasks. Since a logarithmic transformation was used in the modeling process, it is necessary to transform the model to obtain correct units of the response variable. The resulting transformation is shown in Equation 3.

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

$$\text{Position} = e^{(\mu + \beta_i + \gamma_j + \delta \times \text{elevation} + \phi_k + \upsilon_l + \varepsilon_{ijkl})} \quad (3)$$

The resulting model represented by Equation 3 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 10 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 duration of the *Position* task is reduced relative to the mean on projects with the 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 duration of the *Position* task is increased by almost 20%. This can be attributed to the strict enforcement of safety regulations on Project 3. For example, when workers make use of fall protection equipment the duration of the task would tend to increase by approximately 34%. If decking is present in the floor below the workers performing the *Position* task, the duration would be increased by approximately 21%. Elevation of the work area decreases task duration by a factor of 0.9971 raised to the elevation in feet.

Insert Table 10

For example, a project with characteristics similar to Project 3, on which the Position tasks is being performed in the morning hours at an elevation of 9.14 meters (30ft), and where fall protection is being used having decking below the work area, the task duration would increase by 5.96 seconds.

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 factors *Compliance*, *Project*, *Protection Used*, *Deck Present*, and the variables *Temperature* and *Humidity* 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. Equation 4 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. Equation 5 shows the transformed model. The resulting model is also a multiplicative model. Table 11 shows the parameter estimates and the multiplicative terms for the factors in the model. Similarly to the *Position* task, the duration of *Connect* task is higher in the morning hours by approximately 18% (see Table 11). The results also showed that the duration of the *Connect* tasks increases with increasing elevation by a factor of 1.0027 raised to the elevation in feet (see Table 11).

$$\text{Log}\,(\text{Connect}) = \mu + \gamma_i + \delta \times \text{elevation} + \varepsilon_i \quad (4)$$

$$\text{Connect} = e^{(\mu + \gamma_i + \delta \times \text{elevation} + \varepsilon_i)} \quad (5)$$

Insert Table 11

Unhook Task

The factors *Compliance* and *Project* 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 which is a combination of the *Project* and *Compliance* factors. Table 12 shows the levels of the *PCL* factor. When this factor was included in the model it was found to be significant (α=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 factor *Deck Present* and the variables *Temperature* and *Humidity* were not significant in this model. The only interaction observed during the model development process was between the variables *Temperature* and *Humidity*. This interaction was found to be significant but not important. It was a mild interaction that was eliminated since it did not benefit the performance of the model in explaining the effects of the other factors and variables on the duration of the *Unhook* task. However, 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.

Insert Table 12

As with the previous two models, the application of the logarithmic transformation of the data requires a transformation of the model in order to obtain the correct units of time. Equation 7 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 13.

$$\text{Log}\,(\text{Unhook}) = \mu + \rho_i + \varphi_j + \varepsilon_{ij} \quad (7)$$

$$\text{Unhook} = e^{(\mu+\rho_i+\varphi_j+\varepsilon_{ij})} \quad (8)$$

Table 13

The results of the Tukey-Kramer multiple comparison procedure showed that the mean duration of the *Unhook* task was significantly higher (approximately 31%) for projects with characteristics similar to those of Project 3 with no non-compliance 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

14. The results for the *Protection Used* factor show that the duration of the *Unhook* task is approximately 46% higher when fall protection equipment is used ($p<0.0001$).

Table 14

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 3 and 7 seconds on average), the effect of the factors and variables analyzed should not be interpreted as a reason for not using fall protection equipment based on the observed increase in task duration. On the contrary, the results show that safety related factors, such as the enforcement of safety regulations, have a relatively small effect in performance time. Therefore, compliance with safety regulations, such as use of required fall protection equipment is strongly encouraged.

DISCUSSION AND CONCLUSIONS

Safety has traditionally not been included as a primary factor in prior studies on labor productivity. The objectives of this paper were to identify hazards present in steel erection operations and to evaluate how factors related to these hazards can affect the performance time of ironworkers (task durations). The methods used to accomplish the objectives included site observations at seven steel erection projects and ANOVA modeling using one hundred and eighty six observations of task durations in steel erection. The results presented in this paper show that it is possible to quantify the impact of safety and environmental factors on ironworkers' performance by analyzing task duration data. By quantifying the effect that safety practices have on worker performance, modifications to improve performance of constructions processes could be evaluated considering the effects on the safety of the workers. More extensive evaluation of safety equipment could be undertaken to develop equipment that assists workers instead of hindering their productivity.

Workers were observed while performing steel erection tasks and several hazards were identified. The conditions related to the hazard of falls from elevations were used to investigate the effect that these conditions have on the performance of workers in 3 key tasks namely, *Position, Connect* and *Unhook*. Five factors (*Project*, *Time of Day*, *Protection Used*, and *Deck Present*) significantly affected the duration of the *Position* task 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 more factors. The combination of environmental factors, task-related factors, and personal factors (Figure 1) 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. This can be expected since the workers performing these tasks move more and fall protection equipment appears to affect their movement. The environmental variables of time of day and elevation significantly affected only the *Position* and *Connect* tasks. This effect can be attributed to the actions the workers have to perform during these tasks. In the *Position* task workers are required to handle heavy loads while guiding the structural members into the installation point and in the *Connect* tasks they are required to use heavy tools to connect the structural members. The resulting physical exertion and fatigue can affect the performance of the worker by increasing the time required to perform the tasks.

The findings of this study provide evidence of the influence of project management on the use of safety equipment. On projects where management did not establish a formal safety program, safety performance (i.e. use of safety equipment), was lower than on projects that did have a formal safety program. However, on projects on which compliance with safety regulations (i.e. more frequent use of safety equipment) was higher, the performance time of workers was also higher. 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. The effectiveness of project managers in coordinating work to make efficient use of safety equipment should be evaluated. There is room for improvement to safety practices that involve a more extensive use of the safety equipment available, even if there may be perceived increases in task durations. The possible increase in task duration resulting from the use of safety equipment could be offset by: (1) improved quality, (2) reduction in the occurrence of accidents which results in cost savings from reduced insurance premiums, (3) improvements in productivity, and (4) increased competitiveness by having a lower experience modifier rate (EMR).

The role of the safety coordinator is pivotal to the improvement of safety at construction sites. The results of the analysis undertaken in this study showed that on projects that did not have a designated safety coordinator, adherence to safety regulations was lower. There is a need for more involvement of safety coordinators in field operations at the planning and execution levels. Safety coordinators can help workers to understand the importance of being safe while performing their tasks by providing training, supervision, and corrective actions when necessary.

Training, supervision, and coordination of workers can result in increased compliance, improved safety, and improved performance. The results presented in the paper point to the use of safety equipment as a factor that increases the time required to perform steel erection tasks. The observed impact must not be interpreted as a reason to forgo the use of safety equipment, 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.

A restriction of this study was the limited number of observations for each of the variables analyzed. This is typical in observational studies where there is no control over the process being investigated. This limitation could be addressed in future research by designing controlled experiments in simulated environments allowing a larger sample of observations to be collected.

This paper presented the results of an observational study of ironworkers performing steel erection tasks. Hazards present during the steel erection process were identified and the impact of safety related conditions and environmental factors were analyzed. It was observed that task duration averaged 1.3 times longer when fall protection equipment was used and 1.2 times longer with decking installed on the level below the workers. In addition, ironworkers' task duration averaged 1.2 times longer in the morning hours, than in the afternoon hours. These findings demonstrate that safety and environmental factors influence worker productivity and demonstrate the need for research in order to find the causes of these factors. Possible avenues for additional research include the development of improved PPE, and exploring innovative means and methods of construction that improve productivity without negatively impacting the safety of the worker.

SIGNIFICANCE TO RESEARCH AND PRACTITIONER COMMUNITY

The findings of this study demonstrate that a quantitative approach using task durations and safety and environmental factors is a viable alternative to analyze the links between productivity and safety in construction 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 their impact on worker performance. There may be opportunities for additional research in the development of safety strategies that does not hinder worker productivity. The present study is of significance to practitioners in the area of steel erection as it suggests improvements in the area of safety management, especially in the enforcement of safety regulations involving fall protection equipment. Management could also benefit from an integrated construction planning process that takes into consideration the impact that safety practices have on worker performance and plan the work in a way that neither productivity or worker safety is negatively affected.

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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 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.

Table 2 Steel erection tasks

Task	Description
Position	The connector grabs the load to be installed and guides it to the final position where it will be attached to the structure.
Connect	Either one of the two connectors inserts the reamer or spud bar into a bolt hole and then installs the connection bolts. The worker is considered a "connector" only when working with "hoisting equipment". This includes placing components as they are received from hoisting equipment, and then connecting those components while hoisting equipment is overhead.
Un-hook	One of the two connectors instructs the crane operator to lower the hoisting cable to allow the worker to un-hook it, the load is released and the crane returns for the next piece to be installed.

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 • Environmental 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
Presbyterian Church Building in West Lafayette, Indiana	February 2004	• Hazard assessment

Table 4 Projects used for analysis

Project Description	Dates of Data Collection	No. of Observations
Project 1 - 8919 square meters (96,000 square feet), five story addition to existing academic building	April - May 2003	62
Project 2 - Two story dining hall	May - July 2003	71
Project 3 - 17373 square meters (187,000 square feet), three story research facility	September - October 2003	53
Total		186

Table 5 Project characteristics related to safety performance

Project	Characteristics		
	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. • General Contractor had an established safety program. • General Contractor did not mandate that the sub contractor enforce his own safety regulation	• The steel erection company was a medium size company. • 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. • 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. • 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.

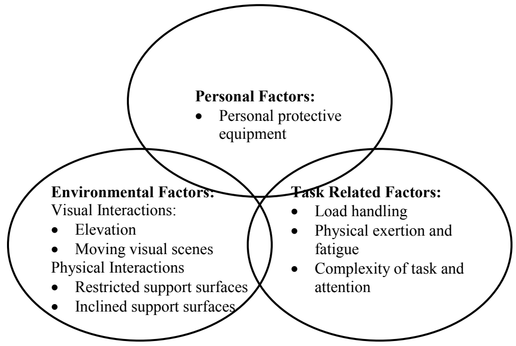

Figure 1 Factors involved in identification of hazards
(adapted from Hsiao and Simeonov, 2001)

Table 6 Conditions related to safety in the steel erection process

Factor	Safety Related Conditions	Definition
1	Use of Fall Protection Required	Were the workers required to use personal protective equipment (PPE) as fall protection? This depends on the elevation while working (according to OSHA Code Subpart R –Steel Erection, Section 1926.760 (a)(1), (b)(1) and (b)(3))
2	Fall Protection Used	Was PPE actually used by the workers?
3	Presence of Decking on Level Below	Was there decking in place on the level below where the workers were located? This requirement is related to Section 1926.754 (b) (3) of OSHA Code Subpart R- Steel Erection. For this rule to apply the difference in elevation between the working location and the level below should be less than the 4.57m (15ft) to 9.14m (30ft) restriction set forth by Section 1926.754 (b)(3).

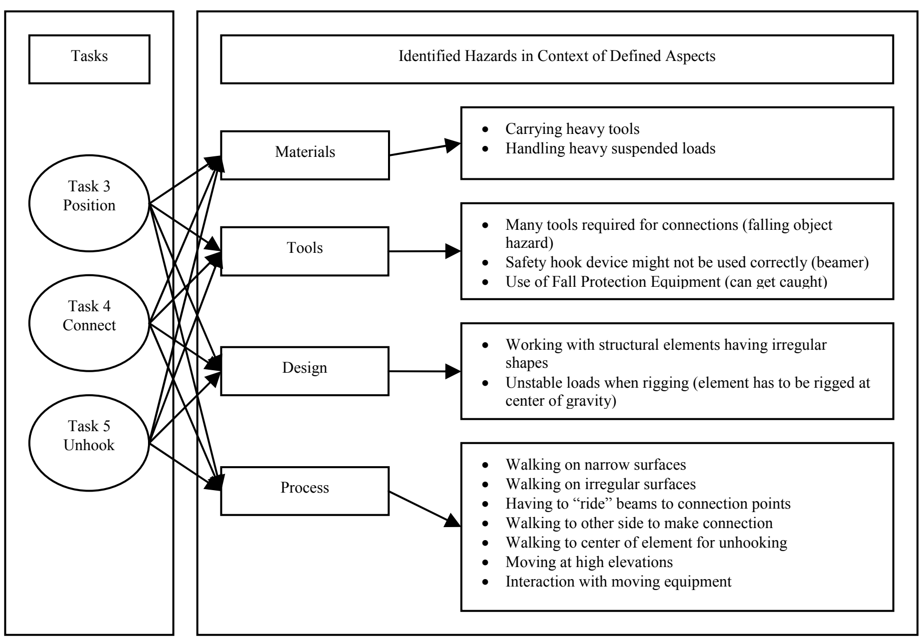

Figure 2 Identified hazards on specific tasks in the steel erection process

Table 7 Safety conditions combinations in steel erection

Case	Description	Safety Outcome
Case 1	Fall protection was required and used, and decking was installed on the floor below	Complies with OSHA Subpart R
Case 2	Fall protection was required and used, and no decking was installed on the floor below	Complies with OSHA Subpart R
Case 3	Fall protection was required and not used, and decking was installed on the floor below	Complies with OSHA Subpart R
Case 4	Fall protection was not required but used, and no decking was installed on the floor below	Complies with OSHA Subpart R
Case 5	Fall protection was not required and not used, and no decking was installed on the floor below	Complies with OSHA Subpart R
Case 6	Fall protection was required but not used, and no decking was installed on the floor below	Does Not Comply with OSHA Subpart R

Table 8 Variables used in the development of the models

Variable	Description
Position	Response variable measured as the duration of the Positions task (seconds).
Connect	Response variable measured as the duration of the Connect task (seconds).
Unhook	Response variable measured as the duration of the Unhook task (seconds).
Temperature (temp)	Explanatory variable. Temperature recorded at the job site during data collection. The unit of measure is ºF. This is considered a quantitative variable.
Humidity (hum)	Explanatory variable. The % 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 (8:00am to 12:00noon) and (0) if the data was collected in the afternoon hours (1:00pm to 4:00pm). 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 one (1) and if the workers were not using the equipment the value was zero (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 one (1) and a value of zero (0) if the deck was not installed. This is considered a qualitative variable.
Compliance (comp)	Explanatory variable or factor. Based of the combination of the "protused" and "deck" variables this variable determines if there was a case of compliance or non compliance 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 non compliance 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 possible effects of variables that can not be easily measured like type of project, safety management practices and others. This factor has three levels, one for each project. Values of (1), (2), and (3) where assigned to the levels.

Table 9 ANOVA 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

*NS = Not significant at α=0.05
*NIM = Not included in model

Table 10 Parameter Estimates and Multiplicative Terms: *Position* Task Model

Factors / Variables	Level Value	Parameter Estimates	Multiplicative Terms
Task Mean (μ)		1.71	5.53 seconds
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*
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

*To apply factor multiply by $e^{-0.0028 x elev} = (0.9971)^{elev}$

Table 11 Parameter Estimates and Multiplicative Terms: *Connect* Task Model

Factors / Variables	Level Value	Parameter Estimates	Multiplicative Terms
Task Mean (μ)		1.9569	7.08 seconds
Time of Day (γ)	i = 0	0	1
Time of Day (γ)	i = 1	0.1638	1.1779
Elevation (δ)		0.0028	1.0028

*To apply factor multiply by $e^{0.0028 x elev} = (1.0028)^{elev}$

Table 12 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

Table 13 Parameter Estimates and Multiplicative Terms: *Unhook* Task Model

Factors / Variables	Level Value	Parameter Estimates	Multiplicative Terms
Task Mean (μ)		1.1287	3.09 seconds
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 14 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	