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ENERGY-BASED SAFETY RISK MANAGEMENT: USING HAZARD ENERGY TO PREDICT INJURY SEVERITY

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Abstract: Worker injuries and fatalities have long been problematic in the construction industry. To address this ongoing concern, recent research has focused on risk-based approaches to proactive safety management. Although the quantity and quality of safety risk data has improved in recent years, available data do not link directly to natural principles and are, therefore, limited in their application and scientific extension. This study offers a new explanation of safety risk using the concept of energy where the underlying proposition is that all hazards are truly defined by the exposure to one or more of ten distinct forms of energy (e.g., gravity, motion, electrical). This concept of safety energy was introduced by William Haddon, was operationalized in a past Construction Industry Institute (CII) research team, and is currently being tested by an active CII research team. The present study aims to link energy transfer to safety risk for the first time. Inspired by natural disaster modeling, the concept of energy is translated to risk by defining the severity of a potential event as the ratio of the magnitude of the energy to the resiliency of the impacted human body part and the pressure exerted on impacted body part. Additionally, the likelihood component of risk is defined by the combination of human, social, technological, and other factors that contribute to the chance that there is an unwanted transfer of energy. To test this proposition, energy-based risk data were extracted from two sources: (1) a random sample of 40 injury reports taken from a larger database containing approximately 7,250 injury reports obtained from 281 private construction organizations and (2) a random sample of National Institute of Occupational Safety and Health Fatality Assessment and Control Evaluation (NIOSH FACE) reports. For each report, a combination of manual and automated content analyses was used to extract the following data: the chief energy source(s) contributing to the incident, the quantity of energy involved, the part of the body affected, and the severity of the outcome. Generalized linear models derived from initial results demonstrate that energy possesses legitimacy in predicting the severity of an injury that will result from a particular hazard, tentatively confirming the proposed theory. This research indicates that energy-based safety risk analysis is a promising line of scientific inquiry with predictive validity that has the potential to increase our understanding of the natural phenomena that contribute to injuries. This research corroborates previous hazard recognition research that introduced the energy principle of hazard classification but challenges the scientific merit of past safety risk data.

1 INTRODUCTION

With an average of more than two fatalities per day, the United States construction industry's 796 workplace fatalities in 2013 accounted for the highest number of workplace fatalities of any United States industry *(Bureau of Labor Statistics, 2014).* The construction industry's disproportionate fatality and serious injury rate has been an ever-present trend which, until the creation of the Occupational Safety and Health Administration (OSHA) in 1970, was largely viewed as an inherently unavoidable characteristic of the work being performed *(Bureau of Labor Statistics, 2014; Cameron et al. 2008; Roudsari and Ghodsi, 2005)*. Current theory, however, is that workplace safety is an indicator of effective design, planning, training, and work execution (Hallowell et al. 2014). Injuries in the construction industry are extremely costly. In fact, Everett and Frank (1996) estimated that the direct cost of accidents account for 15% of the total cost of a project *(Agarwal and Everett, 1997).* In addition to the direct costs, indirect costs such as work stoppage, training replacement workers, repairing damaged property, and maintaining insurance coverage have been estimated to be as high as twenty times the magnitude of direct costs *(Business Roundtable, 1982).* The end result is that the financial impact of workplace fatalities and serious injuries within the construction industry is nearly double that of the all-industry average (*Waehrer et al., 2007)*. Due to the significant humanitarian and financial impacts, improving worker safety within the industry has become an increasingly important priority for construction firms and professionals *(Gambatese et al. 2008).*

Since the creation of OSHA in 1970, researchers and practitioners have introduced a plethora of safety programs such as project-specific training and safety meetings, frequent worksite inspections, and safety and health orientation. However, the effectiveness of these traditional injury prevention approaches is limited due to their reactive and regulatory-based nature *(Hallowell and Gambatese, 2007)*. Additionally, Esmaeili and Hallowell (2012) found that most traditional strategies have reached saturation in terms of new adoption, suggesting that research and development for construction safety is critical for future improvement. In response to these limitations and trends, researchers have begun to explore risk-based practices as a means for safety innovation. Conventional safety risk management methods assume that work can be decomposed into its constituent parts *(Lingard, 2013)*, ranging from broad safety risk analysis of different construction trades *(Baradan and Usmen, 2006)* to detailed safety risk analysis of specific construction activities such as concrete formwork placement (Hallowell & Gambatese, 2009). The problem with this approach, as explained by Cooke-Davis, et al. (2007), is that the decomposition of a complex system such as a construction site is of limited value when the work elements are in constant dynamic interaction with one another. As a result, while helpful, conventional safety risk management methods within the construction industry are limited in terms of both their current application and potential for future scientific development.

The purpose and intention of this study is to address the current limitations in safety risk analysis by offering a new energy-based approach to characterizing the potential severity of injuries. The specific goal is to examine the extent to which the quantity and the type of energy predicts the potential outcome of a hazardous work situation. If a link is established, this study could reveal a more fundamental approach to characterizing and measuring safety risk on construction projects.

2 LITERATURE

Applying the concept of energy to explain safety risk requires an understanding of the concepts of both safety risk analysis and safety energy. In order to better illustrate how this study seeks to advance the cause of safety within the construction industry, the relevant literature is reviewed in these two areas.

2.1 Risk Analysis in Safety Management

In a broad sense, risk can simply be defined as the combination of uncertainty, or probability, weighed against the damage that would be incurred. In the context of occupational health and safety, *risk* is a measure of the likelihood of injury and the associated consequences a hazard present in a given situation (Baradan & Usmen, 2006; Jannadi & Almishari, 2003). In 1984, system safety engineers in the United States military were able to quantify the risk associated with an event as the product of the probability and the severity of an outcome (Quality, 1984). This definition for safety risk, shown in Eq. (1), has remained consistent since its indoctrination and will be the premise for the concept of energy-based safety risk. It should be noted that the probability that a hazard will cause an injury is analogous to the frequency of events within a given period of time. Typically, frequency is expressed in terms of incident rates, whereas the severity is defined in terms of the impact to the work or firm (Hallowell & Gambatese, 2009).

$$[1] \quad Unit\ Risk = (Frequency)\ x\ (Severity)$$

Over the past 15 years, several safety risk quantification methods, varying in complexity and application, have been employed utilizing the underlying concept of unit risk analysis. For instance, Everett (1999) quantified the risk of overexertion injuries for various trades by studying the frequency of particular overexertion injuries incurred while performing work tasks. Similarly, Huang and Hinze (2003) were able to quantify the risk of fall accidents using OSHA and Bureau of Labor Statistics (BLS) statistical data. Several additional studies have since contributed to the advancement of safety risk analysis, quantifying risk for such categories as struck-by accidents (Hinze, Huang, & Terry, 2005), fatalities between construction trades (Baradan & Usmen, 2006), and tower crane activities (Shapira & Lyachin, 2009). The commonality among these studies is that the research focused predominantly on analyzing the frequency of event occurrences to quantify risk. The reasons that safety risk quantification research has primarily focused on incident frequency spans two-fold: 1) frequency data is more easily measured and accessible through databases such as the BLS; and 2) the widely used "Safety Triangle" (Heinrich, 1931) derives its basis on the frequency of events. Nonetheless, the severity component in quantifying risk, which, in its truest sense, is equally as important to likelihood when quantifying safety risk, has not received significant attention in construction safety research. The purposed concept of energy-based safety risk would address this major deficiency and serve as a means to reliably quantify the severity based on the physical characteristics of the hazard.

In comparison to advances achieved in general risk analysis techniques, the development of safety risk analysis methods has lagged due to two fundamental limitations: 1) there is a limited amount of reliable data sources; 2) the employed methods are restricted in their external applications. Of the data sources available, the primary sources used to quantify safety risk include empirical data from private organizations or companies *(Desvignes, 2014; Prades, 2014*), government statistics (Baradan & Usmen, 2006; Hinze et al., 2005), and opinion-based data (Brauer, 2005; J. Everett, 1999; Hallowell et al., 2011; Jannadi and Almishari, 2003). All of these data sources have inherent limitations that reduce the validity and reliability of safety risk assessments. Of all methods, empirical data are preferred because they tend to involve less bias. Unfortunately, researcher access to empirical data gathered by private organizations is limited because they often involve proprietary or confidential information. Although statistics made available through governmental agencies like OSHA and the BLS have provided researchers a credible source from which to develop safety risk analysis strategies, the granularity of government statistics limits risk analysis to the trade, work task, or injury classification level. Widely used in safety risk practices, opinion-based data gathered by industry experts has primarily relied on qualitative risk ratings using numerical or linguistic scales *(Baradan and Usmen, 2006; Brauer, 2005; Everett, 1999; Shapira and Lyachin, 2009).* However, as one might expect, expert opinion data are limited by the personal biases of human raters. For example, *Capen (1976)* revealed that subjective probability is heavily influenced by individual biases and that people have erroneous judgment in statistical intuition under uncertainty. Since *Capen's (1976)* discovery, many other studies have confirmed this debilitating characteristic of expert opinion data *(Gustafson, 1998; Kahneman and Tversky, 1982; Sjöberg, 2000)*. Thus, more robust empirical data must be explored to improve safety risk assessment techniques.

In addition to data source limitations, conventional safety risk management methods are limited in their breadth of application (i.e., external validity). All safety risk researchers assume that the work can be decomposed into its constituent parts in order to address the construction industry's dynamic and transient nature *(Lingard, 2013).* Researchers have used a multitude of techniques to decompose and analyze safety risk, ranging from very high level studies looking at methods to evaluate safety risk amongst different construction trades *(Baradan and Usmen, 2006; Fung, et al. 2010)* and injury classifications (Hinze et al., 2005) to detailed studies looking at specific construction activities and the risk associated with elemental tasks being performed within those activities (Everett, 1999; Hallowell and Gambatese, 2009; Jannadi and Almishari, 2003). However, these risk decomposition techniques are either so overly broad that they have limited application to individual projects or are so specific that any new construction methods or variation upon existing methods requires a laborious research process to collect new data. Very recently, *Esmaeili (2012), Desvignes (2014) and Prades (2104)* explored attribute level risk analysis, which allows one to evaluate risk independent of specific tasks and environments by focusing on fundamental characteristics (e.g., uneven surfaces, work at height, etc.). The present study introduces the energy-level risk analysis strategy for the first time, building upon the new attribute-level theory.

2.2 Energy-Based Safety

The impetus for an energy-based safety approach is the concept of energy-based hazard recognition (*Albert et al., 2014*). According to *Carter and Smith (2006)*, construction workers are customarily poor at identifying hazards during construction because of the industry's diverse, fragmented, and dynamic nature. The inability to identify hazards in turn results in construction workers being exposed to unanticipated dangers or engaging in unsafe work practices without understanding the severity of adverse consequences *(Wilson, 1989).* Taking inspiration from William Haddon's work on safety energy, *Fleming (2009)* sought to improve worker hazard-recognition by categorizing hazards based on the primary energy source that could cause the injury (e.g. motion, gravity, electricity, etc.). *Fleming's (2009)* principal theory is that all construction accidents originate from a specific energy source that is identifiable prior to work. When an energy source is released outside of the work plan, the unanticipated loss of control over the energy source creates the potential for injury. Principles of energy-based safety were soon implemented with respect to hazard recognition by an expert team sponsored by the Construction Industry Institute (CII), which identified and predefined ten energy sources relevant to construction to serve as cognitive cues *(Albert et al., 2014)*. Using a multiple baseline intervention research method with six construction crews, *Albert et al. (2014)* demonstrated a significant 31% improvement in hazard recognition skill amongst workers. Unfortunately, existing literature detailing the use of energy in construction safety is very sparse as the concept of energy-based safety within the construction industry remains in its infancy. However, the initial research results indicate that there is significant promise in using the concept of energy to identify and rank safety hazards encountered in the construction industry.

3 POINT OF DEPARTURE

Current safety risk analysis appears to suffer from two primary weaknesses: (1) a lack of scientifically driven empirical data; and (2) risk analysis strategies which are often narrow in scope, thus limiting their effectiveness when applied to the construction industry's diverse project portfolio. Inspired by energy-based hazard recognition, this study aims to test the null hypothesis that energy has no significant relation to the severity of an injury by offering a new approach to safety risk analysis using the concept of energy to measure the severity of potential hazards, and, by doing so, seeks to introduce natural principals that will allow safety risk analysis to become more universal in its breadth.

4 KEY NEW THEORY

Energy-based safety risk analysis theory draws inspiration from natural disaster modeling which, in essence, predicts the potential impact of a natural disaster by considering the magnitude of the event and the resiliency of the affected area (Johnson, 2004). This same fundamental analytical approach is taken within the context of energy-based safety risk. Specifically, ***energy is translated into severity of a potential hazard as the ratio of the magnitude of energy to the resiliency of the impacted human body part and the concentration of energy transferred.*** The probability, in turn is defined by the various action and inaction that results in the unwanted release and/or exposure to the human body. By quantifying the energy found in these potential hazards, energy-based safety risk analysis may result in a standardized approach to evaluate and predict the severity of potential injuries in any environment, which can subsequently utilize current frequency data techniques with the established principals of Eq. (1) to create a more robust safety risk analysis method Energy within Hazards. When evaluating energy-based safety risk, the magnitude of energy present within a specific hazard must first be determined. To illustrate the concept of energy-based safety risk, consider gravitational potential energy (PE), which depends on the mass and vertical position of an object as shown in Eq. (1), where m = mass; g = gravitational constant; and h = vertical position or height above the ground.

$$[2] \qquad PE = mgh$$

Take, for example, the conditions where both a tape measure and a sledgehammer are dropped on your hand from a height of five feet. Due to their weight differential, intuitively one would expect the sledgehammer to inflict more damage and have a greater potential for breaking bone. Considering energy, this intuition can be scientifically proven. Specifically, a tape measure, which weighs approximately one pound, would only inflict five foot-pounds of energy while a sledgehammer, weighing approximately 15 lbs., would transfer 75 ft.-lbs. of energy. Clearly, under these parameters, the sledgehammer would pose a much higher risk for severe injury; however, a change to one of the parameters can result in the tape measure having the equivalent potential to inflict injury. For example, if the tape measure were dropped from a height of eight stories it would transfer energy in an amount equivalent to that generated by a sledgehammer dropped from five feet, thus transferring equivalent energy to the hand. Thus, according to this new theory, a sledgehammer at a height of five feet and a tape measure at eight stories possess the same potential to inflict injury. Although the prospect of a tape measure being dropped onto a hand from eight stories may seem remote, the concept is very real. Recently, a worker on a New Jersey construction site was fatally injured as a result of being struck by a tape measure which fell from a height of 50 stories (*Santora, 2014*). Although at first seeming comparatively harmless, the tape measure, which weighed approximately one pound, inflicted 500 ft.-lbs. of energy on the worker's head and ultimately led to the worker's death.

4.1 Energy Transfer through Contact Area

Although calculating the energy provides an objective basis from which to quantify and rank most hazards on a particular construction site, further detail is required within the context of how the energy transfers to the human body. Specifically, when considering the severity of injury associated with a moving object, the contact area, or sharpness, must be taken into account. For example, by minimizing the contact area of a knife blade through sharpening, the pressure exerted by the blade is maximized with the same quantity of applied energy. Once translated to force, the ratio of the quantity of energy and the contact area helps to define the true potential damaging factor: pressure. In order to model how energy is linked to pressure one must first consider the concepts of momentum and impulse. Momentum is defined as the product of an object's mass and velocity and impulse, in turn, is defined as the change of momentum per unit of time. The equations for momentum (*p*) and impulse (*J*) are shown respectively in Eq. (3) and Eq. (4), where m = mass; v = velocity; and Δv = change in velocity.

$$[3] \qquad p = mv$$

$$[4] \qquad J = \Delta p = m(\Delta \mathrm{v})$$

It is important to note that the variables used to evaluate momentum and impulse are identical to kinetic energy (KE) as shown in Eq. (4), where m = mass and v = velocity, and which, as a result of conservation of energy, can easily be found using Eq. (1) for potential energy.

$$[5] \qquad KE = 1/2mv^2$$

The final step in determining the severity of a potential hazard is to ascertain the pressure, defined as force per unit area, exerted by the energy source. By using Newton's second law of motion, where force is the product of mass and acceleration, and the principals of momentum and impulse, variables used to calculate an object's energy can be substituted and used to find pressure (P) as shown in Eq. (5), where F = force; A = area; m = mass; v = velocity; a = acceleration; Δv = change in velocity; and t = time.

$$[6] \qquad P = \frac{F}{A} = \frac{ma}{A} = \frac{m\Delta v}{\Delta t A}$$

In order to illustrate the relationship between pressure and the severity of a sustained injury, the one-pound tape measure provides a compelling example. It was determined that dropping this tape measure from a height of five feet was relatively harmless, exerting approximately 5 ft.-lbs. of energy. Replacing the tape measure with a concrete chisel of equal mass (1 lb) and dramatic differences in damage would be sustained because of the sharpness of the concrete chisel. Assuming the respective impulse durations and final velocities of the two objects have equivalent values of 0.05 seconds and 17.9 ft/s, the tape measure, landing on its end, would have an estimated contact area of $2\ in^2$, thus exerting a pressure of about 5.6 psi. By comparison, the concrete chisel, with an estimated contact area of $0.01\ in^2$, would exert a pressure of 1121 psi. Although the concrete chisel and tape measure possess an equivalent amount of energy, the large disparity in contact area between the objects caused a drastic increase in the injury suffered by your hand. For this reason, the contact area, or sharpness, of a hazard must be accounted for in evaluating the potential severity of an outcome.

4.2 Resiliency

Using the analogy of natural disaster modeling, the magnitude of a natural disaster, such as a hurricane, does not fully predict the magnitude of damage. For example, due to differences in infrastructure, a hurricane striking the coast of Haiti would presumably inflict more damage than a hurricane striking the coast of Florida. This concept, referred to as resiliency, also applies in the context of energy-based safety risk where the extent of injury caused by a particular hazard varies depending upon the resilience of a particular body part to the energy transferred or pressure inflicted. For example, if the unfortunate New Jersey construction worker had been struck by the tape measure in the shoulder rather than his head, his injury would almost certainly have not been fatal. In summary, the resiliency of the particular body part involved is a critical factor in predicting the outcome of a hazard event, and thus must also be taken into account when evaluating safety risk using energy.

4.3 Conceptual Framework for Energy-Based Safety Risk

A conceptual framework has been formulated to evaluate the safety risk for gravity, motion, mechanical, and electrical energy sources. The rationale for including these energy sources is that they are associated with the four leading causes of worker fatalities in the construction industry (falls, struck-by, caught in/between, and electrocution), known a as the “fatal four” *(Bureau of Labor Statistics, 2014)*. The conceptual framework, which is illustrated below in Table 1, builds upon the principles of energy, pressure, and contact area previously discussed. With the exception of the body part impacted, the inputs into the conceptual framework are all objectively measurable hazard factors such as mass, height/speed, sharpness, and voltage of observable physical objects. To simply illustrate relative magnitudes and mechanisms by which a severity score can be established, one may consider the each variable on a 1-3 scale, with 1 representing a low quantity and 3 representing a high quantity. The final component included in an energy-based risk score is the affected body part. Rating the affected body part is based on the resiliency levels of different body parts and is also scored on a scale of 1 to 3, with 1 representing a less critical body part such as a hand and 3 representing a more critical body part such as the head. The Severity Score is calculated by Eq. (7), resulting in a range from 1 to 81. It should be noted that the conceptual framework set forth below is preliminary in nature and, as such, the hazard factors used the simplistic 1-3 rating scale in addition to being weighted evenly for purposes of illustration only. As further analysis is performed, the conceptual framework can be readily adjusted in a variety of ways to provide for a greater degree of precision; for instance, the use of actual, physical values for the measurable factors in the place of rating scales.

$$Severity\ Score = (Mass)\ x\ (Height)\ x\ (Sharpness)\ x\ (Body\ Part) \quad [7]$$

Table 1: Examples of various cases using the energy-based risk analysis method

Mass	Height (or Speed)	Sharpness	Criticalness of Body Part	Severity Score (1-81)	Description
1	1	1	1	1	*Tape Measure Dropped from 5 ft. onto hand*
1	3	1	3	9	*Tape Measure Dropped from 50 stories onto head*
1	3	3	3	27	*Concrete Chisel Dropped from 50 stories onto head*
3	3	3	3	81	*W-Flange Beam Dropped 50 stories onto head*

5 METHODS

The objective of the analysis is to test the proposed theory by investigating the relationship between the severity of worker injury and the energy present before the injury was sustained. To achieve this objective, samples of injury reports spanning a three year period were taken from a database consisting of 7,250 injury reports obtained from 281 private construction sources. Reports with sufficient detail to quantify the elements in Table 1 were extracted. Using a system established by Hallowell and Gambatese (2009), the severity of various injury outcomes was classified and assigned a relative rating. The injury classifications, as well as their respective definitions and "relative impact scores", employed in this system are listed in Table 2.

Table 2: Injury Outcome Classification, Definition, and Relative Impact Score

Classification	Definition	Severity Score
1st Aid	Any treatment of minor scratches, cuts, burns, etc. where the worker is able to return to work following first-aid treatment	48
Medical Case	Any work-related injury or illness requiring medical care or treatment beyond first-aid where the worker is able to return	138
Lost Work Time	Any work-related injury or illness that prevents the worker from returning to work the following day	256
Permanent Disability	Any work-related injury or illness that results in permanent aliment	1,024
Fatality	Any work-related injury or illness that results in death	26,214

**Footnote ~ Average Relative Impact Scores were used for Medical Case and 1st Aid*

Despite the relatively large database of text reports from past injuries, the sample size used in the analysis was comparatively limited because fatalities and disabling injuries were (fortunately) rare. To compensate for this limitation, fatality reports were chosen at random from the National Institute for Occupational Safety and Health's (NIOSH) Fatality Assessment and Control Evaluation (FACE) program. Even so, a lack of injury reports involving the "Permanent Disability" outcome were sparse, and consequently removed from this preliminary analysis on the basis of having an insufficient sample size. Ultimately, the resulting sample size was 40 injury reports, involving 10 injury reports chosen at random for each respective severity level (excluding "Permanent Disability") in order to maintain consistency for comparison purposes. Once the reports were extracted and compiled, the energy source associated with the hazard involved in each injury report was assigned using either kinetic, potential, or rotational energy techniques. Unfortunately, due to the lack of detail in the injury reports, estimations of object height, speed, and weight were often necessary. To minimize bias, at least two researchers conducted independent assessments.

6 RESULTS AND ANALYSIS

To assess the relationship between accident severity and the magnitude of energy involved in a particular incident, the resulting energy data were compared to the respective severity scores for each injury. By examining the raw distribution of energy contained in the various severity levels, one can see a correlation between the amount of energy involved and the severity level of each outcome (see Figure 1, Figure 2 and Table 3). Because the severity scale and the quantity of energy follow a power distribution, a power regression model was created and confirms a strong correlation, having an R^2 value of 0.69. However, although an increase in energy level appears to be positively correlated to the severity of an outcome, there is a wide variability between the various energy levels contained within any specific injury classification. The variability in energy at each severity level relates to the importance of pressure and resiliency as previously discussed. For example, the two injury reports that represented the maximum and minimum amount of energy under the *fatality* classification involved a 40 ft. crane boom section falling onto a worker and a worker hitting his head after falling 10 ft. off of a ladder, respectively. The crane boom was found to have approximately 40,000 ft.-lbs. of energy, while the worker on the ladder only had 1500 ft.-lbs; however, both incidents were fatal. In addition to the wide variability of energy found within each corresponding severity level, the ranges of energy between corresponding severity levels had significant overlap (see Figure 2). Much like the variability within severity levels, the overlap between severity levels is explained through resiliency and pressure. For instance, the injury report that possessed the highest amount of energy for the *1st Aid* severity level and the two lowest energy situations for the

Medical Case and *Lost Work Time* severity levels possessed nearly an identical amount of energy. The respective outcomes for these 1st Aid, Medical Case, and Lost Work Time injury reports were a 2x4 hitting a worker in the back causing a minor contusion, a worker hit his head on a steel pipe, leaving him temporarily disoriented, and a steel pipe struck a worker's fingers, breaking two fingers. Although these injury reports only varied by 20 ft.-lbs from one another, the three situations possessed very different outcomes due to the factors of resiliency and pressure. Initial results indicate that areas where the energy of severity levels overlap are heavily influenced by resiliency of the human body part effected as well as the pressure exerted on that body part (as indicated on Figure 2, where medical case and lost work-time overlap). Note that there is no overlap between first aid and fatality. These results tentatively confirm the proposed theory, demonstrating that the energy of a hazard has predictive validity in determining the severity of an injury.

Table 3: Mean, Median, and Standard Deviation

	$\bar{x}$ (ft.-lbs.)	$\tilde{x}$ (ft.-lbs.)	s^2 (ft.-lbs.)	Min. (ft.-lbs.)	Max (ft.-lbs.)
1st Aid	21	18	16	3.9	58.5
Medical Case	199	109	186	49	585
Lost Work Time	1093	1023	919	40	2407
Fatality	10818	4403	13245	1500	40000

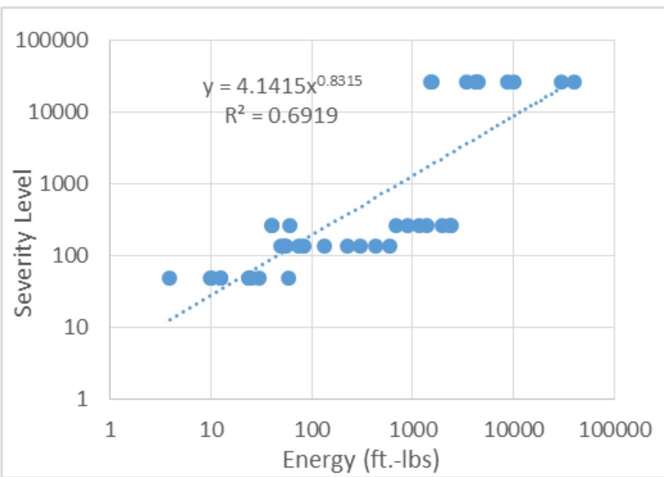

Figure 1: Severity Level vs. Energy (Raw Distribution)

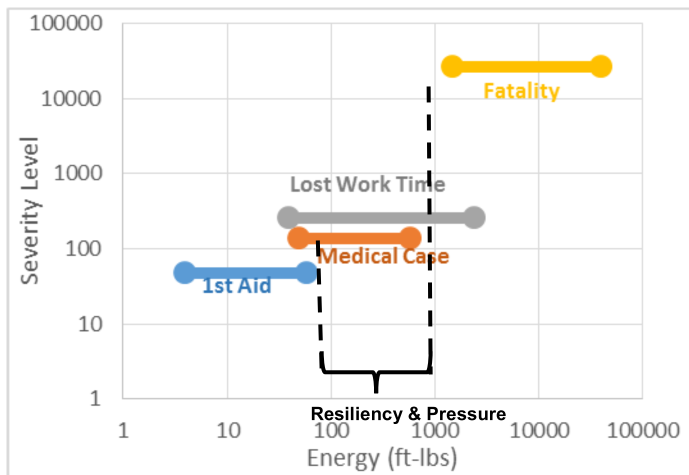

Figure 2: Severity Level vs. Energy (Raw Value Range)

7 CONCLUSION

To reiterate, the purpose of the research was to test the null hypothesis that energy has no significant relation to the severity of an injury. In order to test the null hypothesis, a theory using the concepts of energy, pressure, and resiliency was introduced and tested using a sample of40 reports randomly extracted from a database containing 7,250 injury reports obtained from 281 private construction organizations spanning a three year period as well as NIOSH's FACE database . Despite considerable variability in energy data within injury classification levels, statistical and regression analysis indicate that energy may have significant predictive capability in relation to the severity of an injury outcome, thus tentatively confirming the proposed theory. Although the research provides the preliminary evidence of energy's predictive validity, the study performed possessed limitations. Most notably there was a lack of detailed data for fatal and disabling injuries. The injury reports used for analysis were sufficiently detailed for this analysis. Future researchers, however, could find greater levels of detail by increasing the breadth of the reports analyzed. Furthermore, the study only included three of the ten identifiable energy forms on a construction site (gravity, motion, and mechanical). Supplementary exploration needs to be conducted regarding other hazardous energy sources in addition to more detailed research exploring the energy sources used in this study.

The inspiration for assessing whether energy can be useful in predicting the severity of an injury arose mostly from the CII-funded work of Albert et al. (2014), who were recently able to improve deficiencies in worker hazard recognition by using the concept of energy to better identify hazards. The safety risk practices currently employed within the construction industry share flaws similar to those of past hazard recognition techniques in that they lack scientifically driven empirical data and are narrow in scope, thus limiting the effectiveness of these practices when applied to the construction industry's diverse project portfolio. By introducing the concept of energy into safety risk analysis within the construction industry, the goal and intention would be to improve upon these two weaknesses.

According to Lingard (2013), safety risk analysis is based upon decomposing construction activities and hazards in order to quantify risk. The concept of energy builds on this view by breaking down hazards to their most elemental form, thus making energy, when combined with probability data, theoretically translatable to nearly every construction project or activity. The initial research results indicate that energy has significant potential for predicting the severity of an injury. The outcome was that energy-based safety risk analysis shows significant promise in becoming a much improved and more universally accessible technique for safety risk analysis within the construction industry. If developed to its full potential, indications are that use of energy-based safety risk analysis will allow practitioners to more accurately model and respond to hazards as they are introduced and removed from a work environment. The method may also have application to BIM where energy may be calculated during work sequencing and work packaging.

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