Relationship between Construction Safety and Quality Performance

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Abstract: It is well established that the project cost, quality, safety, and duration are the four critical elements that contribute to project success. Past literature has established theoretical relationships between construction safety and quality on the basis of opinions of industry experts. This is the first empirical inquiry into the relationship between safety and quality, testing the null hypothesis that there is no statistical relationship among quality performance indicators and safety performance indicators. To test this hypothesis, empirical data were collected from 32 building construction projects, ranging in scope from \$50,000 to \$300 million dollars. Several quality metrics (e.g., cost of rework per \$1M project scope and rate of rework per 200,000 worker-hours) were used as predictor variables and first aid and Occupational Safety and Health Administration (OSHA) recordable injury rates were used as response variables. Linear regressions among the predictor and response variables showed that there are two statistically significant relationships: the OSHA recordable injury rate is positively correlated to rework ($r^2 = 0.968$; p-value $= 0.032$) and the first aid rate is positively correlated to number of defects ($r^2 = 0.548$; p-value $= 0.009$). To understand why these relationships exist and to identify specific strategies that promote both safety and quality, open-ended interviews were conducted with project managers. These individuals indicated that the most compelling reason for the strong positive correlation between rework and injuries is the fact that rework involves demolition, schedule pressure, and unstable work processes. They also noted that devoting resources to preplanning, allowing the necessary time to complete tasks correctly the first time, encouraging leadership at the workface, and encouraging workers to take pride in their work are all strategies that promote both safety and quality. **DOI:** 10.1061/(ASCE)CO.1943-7862.0000732.

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Introduction

Construction is a dangerous business. In 2010, the industry accounted for more fatalities than any other industry in the United States (Bureau of Labor Statistics 2011). Additionally, construction injuries are expensive and account for over \$8 billion in direct costs each year (Center for Construction Research and Training 2008). Construction safety researchers have continued to call for further safety improvements (MacCollum 1995) and, in the last 30 years, many have endeavored to create or disseminate knowledge that enhances safety performance. Researchers have investigated safety at a number of levels, including microlevel personal factors such as personal distractions that lead to fatalities (Hinze 1997), project-level factors related to the immediate physical environment such as work visibility and heavy equipment (Hinze and Teizer 2011), and the organization-level factors like culture (Mohamed 2002). Most recently, researchers have set their sights on higher-level systematic factors such as the interplay between construction safety and design (Gambatese et al. 2005) and safety knowledge management (Hallowell 2012). Despite the wealth of construction worker safety and health literature, injuries and illnesses continue to occur at alarming rates.

It is well established that the project cost, quality, safety, and duration are core elements that contribute to project success. Construction organizations tend to invest in management strategies that enhance performance in all of these areas. Unfortunately, when resources are limited, investments must be prioritized and may be in conflict. For example, Hinze and Parker collected empirical data that showed that an increase in schedule pressure decreased safety performance (Hinze and Parker 1978). This finding is supported by other theoretical and conceptual models like that presented by Mitropoulos et al. (2005). Additionally, Hallowell (2011) found that suboptimal safety investments will yield higher injury rates and costs related to safety (Hallowell 2011). Thus, organizations that wish to enhance budget performance by cutting safety costs may see additional injuries and associated expenses. Finally, there is a general understanding of the financial implications of project delays. For example, the relationship between time and cost is

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explicitly considered in liquidated damages clauses. Despite this wealth of literature, the relationship between construction quality and safety performance represents a significant knowledge gap. As will be discussed, some studies have provided anecdotal evidence that there is a positive correlation; however, no studies have examined empirical relationships or explained why this relationship has been observed on actual projects. Thus, this study adds to the body of knowledge by collecting and analyzing empirical data from a representative sample of recent projects.

It was important to establish operational definitions for quality and safety. Construction quality is defined as the conformance to the customer requirements documented through plans, specifications, contracts, and applicable codes and standards (Ashford 1989). Construction rework is a typical indicator of construction quality, as it measures activities required to repair defective products and achieve the required performance specifications [Construction Users Roundtable (CURT) 2005]. On the basis of a comprehensive literature review, Love (2002) reported several measures of rework, including quality deviations (Burati et al. 1992), nonconformance (Abdul-Rahman 1995), defects (Josephson and Hammarlund 1999), and quality failures (Barber et al. 2000). Hence, the primary indicators of construction quality are percent cost of rework and rate of construction defects. The American Society of Safety Engineers (ASSE) defines construction safety as the "state for which the risks associated with the work are acceptable and tolerable in the setting being considered" (Manuele 2008, p. 30). The Occupational Safety and Health Administration (OSHA) recordable injury rate and first aid injury rate are typical measures of construction safety performance.

To establish a testable hypothesis grounded in theory, the authors reviewed the body of literature that discusses the relationship between safety and quality. A number of researchers have proposed theoretical relationships. For example, Pheng and Pong (2003) and Pheng and Shiua (2000) propose frameworks for integrating quality and safety management systems. These researchers noticed the similarity between safety management and quality management programs and suggest that combining the two would result in more efficient use of limited resources. Similarly, Loushine et al. (2004, 2006) found that safety management plans are similar in structure and content to those of successful quality management plans in that they both address proactive management of risks that impact project success. Additionally, Husrul et al. (2008) found positive relationships between quality and safety in Total Quality Management (TQM) programs and stated that safety leads to quality. Though combining safety and quality systems may be an excellent management strategy, these studies fail to capture the direct relationship between safety and quality or test their models on actual worksites. In fact, in a thorough literature review, Loushine et al. (2006) noted a distinct lack of empirical studies on the topic.

Two recent studies have used opinion-based data to explore the relationship between quality and safety. First, Hatush and Skitmore (1997) used the Delphi method to correlate factors in contractor selection, including quality and safety. Although they did not specifically investigate the correlation between safety and quality, their use of qualitative scales as a proxy measure for project quality is relevant to this paper. During the study, the following four safety factors were analyzed against a three-point qualitative rating proxy of project quality: safety performance, experience modification ratio (EMR), OSHA incidence rate, and management safety accountability. Second, in a recent study, Hoonakker et al. (2010) conducted interviews with contractors and found that when they implement quality management systems, safety can be a potential benefit. Again, these studies provide excellent qualitative evidence for a positive relationship between the two performance metrics, but no studies have provided empirical evidence or specific observations that support this theory.

Point of Departure

The body of literature provides strong qualitative support for a relationship between safety and quality performance. However, past studies have yet to provide an empirical connection between quality and safety. This paper addresses this knowledge gap by collecting quality and safety performance data from recently completed projects and correlating the performance metrics. To better understand why there is a connection between quality and safety on the sample of projects, the authors obtained subjective data through interviews with project managers.

Background

To develop context for this inquiry, the authors reviewed literature related to the causes of construction defects and construction injuries. This literature review codified the upstream factors that cause these contingent liabilities and aided in our interpretation of results.

Causes of Rework

Early research in rework addressed an industry need to improve construction quality. The first step was to systematically measure the costs incurred through nonconformance (Davis et al. 1989), which deals specifically with defects and rework as a metric for quality. After discovering that the cost of nonconformance was between 2.3% and 9.4% of the total project costs (Josephson and Hammarlund 1999), researchers renewed their interest in examining the root causes of rework in hopes of reducing costs.

Several studies have identified general causes of defects and rework. Most notably, Love and Li (2000) investigated the major causes of rework in construction and found that changes initiated by the client and end user, together with errors and omissions in contract documentation, were the primary causes of rework. Hammarlund and Josephson (1991) reported that the major causes of quality failures in order of precedence are defective workmanship, defects in products, insufficient separation, inadequate construction planning, disturbances in personnel planning, delays, alterations, failures in setting-out, and coordination failures. In summary, rework can result from errors, omissions, failures, damage, and change orders throughout the procurement process (Love et al. 1999; Love and Li 2000).

The previously identified causes of rework fall into several categories that span systematic, organizational, and individual-worker levels. On a systematic level, researchers have indicated that the design stage is a major source of rework, with as much as 79% of rework created during design (Burati et al. 1992). This is why Davey et al. (2006) suggests that defects could be reduced through design changes early in project development. Most recently, researchers have taken a systems view and theorized that causal factors such as schedule pressure and client requirements combine with technical issues and cognitive mistakes to produce rework (Love et al. 2008). The distinguishing characteristic of these studies is the implication that rework is caused by forces that are external to construction itself, namely the design.

On an organizational level, authors identify theoretically manageable factors related to rework. For instance, Hammarlund and Josephson (1991) attributed production errors to site management. The authors revisited the topic, identifying the origin of defects as being production-based (54%), site management-based (34%), and workmanship-based (20%) (Josephson and Hammarlund 1999). Along those same lines, other authors have identified poor communication as a cause of rework, claiming that a lack of understanding the end user requirements causes defects (Love and Edwards 2004b). One author briefly mentions procurement delay as a cause of rework (Arain et al. 2004), whereas other researchers claim that rework results most often from work changes (Sun and Meng 2009). In any case, the organizational level studies on rework cite causal factors that the builder can control and are internal to the construction and planning process.

Another theme in quality research is investigating the cognitive errors that lead to rework. Several of these studies focus on managerial influences (Atkinson 1999) and how latent managerial errors underlie obvious operative errors (Atkinson 2002). This approach is fairly intuitive, because it places the root cause of organizational management issues on management. Josephson and Hammarlund (1999) further classify these types of behavior into motivation-, knowledge-, and information-based errors.

Together these studies provide a broad base on which to understand the causes of rework; however, there are very few instances where safety is mentioned in tandem with rework. Love and Edwards (2004a) provide a notable exception, stating that, “It would appear, however, that as rework costs increase, safety is perhaps compromised as the pressure to complete the project on time and to budget increases. Safety should not be overlooked and precautionary measures must be implemented when a project is running behind schedule and over budget.”

Although there is an extensive body of literature related to rework, the majority of empirical research on the causes of rework examines the impact of rework on cost data and other project metrics in an effort to determine monetary loss associated with rework (e.g., Josephson and Hammarlund 1999). Although this is a very valuable strain of research, project performance falls short as a holistic measure of success, with safety predominately being left out. Although some researchers are attempting to take a more holistic view of rework, the existing body of knowledge lacks an empirical study that relates measures of quality to safety metrics.

Causes of Injuries

Following the Occupational Safety and Health Act of 1970, numerous attempts have been made to improve understanding of the causes of injuries and the methods of prevention. Two types of studies have emerged to explain the causes of injuries. The first class of studies focuses on theory that explains the general causes of injuries and has been developed by integrating concepts from psychology, sociology, engineering, and systems analysis. The second group of studies attempts to explain the causal factors for specific injury types on the basis of a situational analysis of the tasks performed or environments experienced by the workforce (e.g., Huang and Hinze 2003). For the purposes of this study, only theoretical studies that explain general causes of injuries are examined.

Most accident causation theories have been established by researchers in the occupational safety and health or psychology domains, which is independent from any one industry. The strength of these theories is that they are applicable to many work scenarios and help researchers and practitioners understand the fundamental physiological, managerial, logistical, and systematic reasons why injuries occur. Nearly all conceptual models are based on the underlying theory that injuries are caused by the simultaneous presence of two primary factors: unsafe conditions and unsafe actions (Heinrich 1959; Reason 1990; Hinze 1997; Gibb et al. 2004). This concept was extended by the Naval Surface Weapons Center to include secondary factors such as design and management errors in the Chain of Events Theory (Fine 1975 as cited in Hinze 1997). In this theory, the cause of an injury is said to be the result of a failure or series of failures in the design, coordination, management, or execution of work. The model does not, however, name these deficiencies in the system; rather, it provides a conceptual framework for explaining the cause of an injury once it has occurred.

Two advanced conceptual models have been established. First, Reason (1990) used psychological theory of human error to form the “Swiss cheese model,” a conceptual model in which each preventative method is represented as an impermeable layer and each deficiency in the safety system as a hole in the respective layer. According to his theory, injuries occur as the result of a trajectory when the deficiencies (i.e., holes in the Swiss cheese) align. Second, Mitropoulos et al. (2005) described injuries using a systems model in which they assumed that injuries are caused by many interrelated factors. This model included a small number of common risk factors and mitigation techniques and the direction (positive or negative) of their relationships. The systems model considers risk factors such as unpredictability of task and condition, production pressures, tendency for competent action, and errors and changes in conditions. A number of these factors overlap with the causal factors of rework, yet safety and quality have not been studied together. Additionally, the systems model of injury causation proposes relationships between interrelated factors, but does not provide empirical evidence for these relationships. These models pave the way for quantitative studies to validate relationships between causal factors.

Several of the preceding models mention design as a factor inherent to construction safety, but only recently have researchers begun to examine the possibility of designing for safety. Initially, researchers identified a number of design characteristics that would dramatically improve worker safety and integrated them into a computer based design toolbox (Gambatese et al. 1997). Further research indicated that a significant portion of construction accidents happen during design and planning stages before construction even begins (Suraji et al. 2001), which further confirms the need to alter design to improve safety performance. To emphasize this point, a more recent study examined 224 National Institute for Occupational Safety and Health (NIOSH) fatality investigation reports and qualitatively linked fatalities to causes that could have been prevented by the design for safety concept using content analysis. The study concluded that 42% of fatalities in construction could be eliminated or reduced by designing for safety (Behm 2005). Gambatese et al. (2005) examined the viability of designing for safety, concluding that it is a viable intervention in construction. Although these studies provide valuable evidence that design has a significant effect on safety performance, the link between design stability and safety has yet to be explored. These strains of research focus on elements of the final design, not the design process itself.

Research Methods

Data were collected in three complementary steps to enhance the internal validity, external validity, construct validity, and reliability. First, empirical data were collected from 32 construction projects located mostly within the United States. These projects were performed by 24 different organizations ranging from $120 million to $3 billion in annual revenue (average $450 million). Second, project managers from these projects were asked to share their opinions regarding the performance of the case project relative to past projects completed by their organization. Third, if project managers felt that there was a relationship between safety and quality, they were asked to describe actual observations that explain *why* the observed relationship exists and elucidate the management strategies that promote both safety and quality. All data were ultimately obtained from project managers on active projects and the unit of analysis was the project.

Potential projects were identified through a convenience sample of personal contacts, members of the Associated General Contractors (AGC), and members of the Construction Industry Institute [CII (1989)]. The lack of a random sample results in limitations to the external validity of the conclusions; however, the strong theoretical foundation provides strong support for the extension of these findings beyond the sample. The sample included a variety of project types distributed across the United States with an average total scope of $37 million. Less than half of the projects had a total scope larger than $20 million.

In total, data were gathered from 32 projects, with 26 located in the United States (81%) and six projects (19%) located internationally. The scope ranged from $50,000 to $300 million dollars. For 12 of the 32 projects (37%), the construction work was in progress at the time of the study, with the remaining 20 projects (63%) recently completing construction. Although 32 projects provided data for the study, some could not provide safety and quality data for all measures. After eliminating projects that did not report either safety or quality data, there were 18 remaining data points.

Empirical Data and Hypothesis Development

To collect empirical data for valid, unbiased hypothesis testing, an interview template was created that included a set of demographic, project performance, and open-ended questions. All interviews were conducted in person or over the phone. The following demographic data were obtained from each project: location, scope (in U.S. dollars), percent complete, worker-hours accumulated, delivery method, contract method, project type, and whether the project is union or open shop labor. Additionally, project performance data were requested, including the number of first-aid injuries, number of OSHA recordable injuries, number of defects, cost of rework, and number of worker-hours spent on rework.

Safety Performance

When collecting and analyzing safety performance data, the authors adopted the Occupational Safety and Health Administration's definitions of recordable and first-aid injuries to ensure consistent metrics. The OSHA recordable injuries are defined as any injury that results in death, days away from work, restricted work or transfer to another job, medical treatment beyond first aid, or loss of consciousness. First aid, on the other hand, are those injuries that require one-time treatment and subsequent observation of minor injuries such as cleaning wounds on the skin surface; applying bandages; flushing an eye; or drinking fluids to relieve heat stress. The data sets refer to the following two safety measures:

- INJ1—OSHA recordable injury rate (OSHA recordable injuries per 200,000 worker-hours); and
- INJ2—First-aid injury rate (First-aid injuries per 200,000 worker-hours).

As is expected in any broad data sample, some project managers did not collect or have access to some data. Of these 32 projects, 18 reported on both safety and quality. The raw data for these 18 projects are included in Tables 1 and 2.

Quality Performance

Information about the total number of defects/rework (units needing rework), the total cost of rework, and the total hours related to rework was requested. The authors were able to obtain complete rework data from 17 projects. Twenty-one project managers reported data on the total cost of rework, which ranged from $2,000 to $569,000. Finally, for 23 projects, the number of worker hours related to rework was obtained, ranging from 24 to 4,750 h. All of these values were converted to rates using the project scope and total number of worker hours accumulated as the denominators. The following six quality measures were developed:

- Q1—Number of defects per $1 million project scope completed;
- Q2—Number of defects per 200,000 worker hours;
- Q3—Cost of rework per $1 million project scope completed;
- Q4—Cost of rework per 200,000 worker hours;
- Q5—Number of worker hours spent on rework per $1 million project scope completed; and
- Q6—Number of worker hours related to rework per 200,000 worker hours.

Table 1. Summary of Project Demographics

Project name	Project location (city, state)	Delivery method	Contract method (e.g., lump sum)	Project type	Union or open shop labor	Total project scope ($)	Percent complete (%)	Number of worker-hours accumulated	Number of first aid injuries
Project 1	Colorado	DBB	Cost plus	Commercial	Open	8,610,209.00	100	103,040	5
Project 2	International	DBB	Lump sum	Residence	Open	159,207,662.00	89	560,136	1
Project 3	Colorado	DBB	Cost plus	Commercial	Open	4,365,332.00	100	58,880	2
Project 5	Colorado	DBB	Cost plus	Commercial	Open	1,544,099.00	100	32,200	4
Project 6	California	DB	Lump sum	Government	Both	77,000,000.00	100	393,000	3
Project 11	Wisconsin	DBB	Lump sum	Commercial	Union	600,000.00	100	2800	1
Project 15	California	DBB		Commercial	Open	3,200,000.00	100	43,000	9
Project 16	California	DBB	Lump sum	Industrial	Open	2,300,000.00	100	9,600	2
Project 20	Colorado	DBB	Unit price	Heavy civil	Open	1,881,052.00	100	11,133	1
Project 21	International	DB	Lump sum	Commercial		87,208,645.00	61	398,456	0
Project 23	Colorado	DBB	Unit price	Heavy civil	Open	26,500,000.00	100	215,290	10
Project 25	Colorado	DBB	Lump sum	Institutional	Open	6,415,000.00	100	74,000	1
Project 26	International	DBB	Lump sum	Residential		293,051,919.00	85	688,587	1
Project 27	International	DBB	Lump sum	Commercial	Union	23,925,890.00	60	65,680	9
Project 28	International	DBB	Lump sum	Residential	Open	24,393,812.00	59	66,935	11
Project 29	International	DBB	Lump sum	Institutional	Union	57,115,829.00	70	1,081,600	8
Project 30	Texas	DBB	Lump sum	Commercial	Open	1,080,500.00	100	19,200	4
Project 31	Colorado	DB	Cost plus	Commercial	Open	6,041,000.00	100	10,328	1

Note: DBB = design-bid-build; DB = design-build.

Table 2. Summary of Project Level Safety and Quality Performance

Project name	Number of OHSA recordable injuries	Total number of defects/rework (units needing rework)	Total direct and indirect cost of rework	Number of worker-hours related to rework
Project 1	0	5	$70,000.00	1000
Project 2	1	100	$53,571.43	880
Project 3	0	3	$12,000.00	200
Project 5	0			3000
Project 6	4		$569,000.00	
Project 11	0	1	$10,000	160
Project 15	2		$2,900.00	72.5
Project 16	0	3	$12,500.00	2550
Project 20	0		$2,542.00	44
Project 21	1	70	$41,000.00	524
Project 23	6	10	$123,500.00	1100
Project 25	0	6		200
Project 26	0	70	$59,555.56	592
Project 27	1	18	$132,000.00	248
Project 28	0	20	$18,450.00	29
Project 29	0	16	$6,250.00	4750
Project 30	0		$12,103.00	210
Project 31	0	2		104

Table 3 presents the summary of the various quality and safety measures that we used to study the relationship between construction safety and quality performance.

Hypothesis Development

Although a number of different safety and quality measures are examined, these variables only measure three concepts. Both INJ1 and INJ2 examine safety from the perspective of recorded worker injuries of varying severity. On the other hand, there are two basic measures of quality that were deemed relevant, the first of which is defects as evaluated by Q1 and Q2, the second of which is rework as measured through Q2, Q4, Q5, and Q6. Because these measures compress into three distinct concepts, two fundamental hypotheses were developed:

- H1: There is a relationship between rework and safety.
- H2: There is a relationship between defects and safety.

These hypotheses have been restated as null and alternative hypothesis in Table 4 along with their independent and dependent variables.

Supporting Opinion-Based Data

The empirical data were supported by the collection of project managers' opinions of project safety and quality performance. The empirical data were the focus of this study, and the opinion-based data were only collected to support the empirical results. However, the opinion-based data provide an important link to the existing studies of safety and quality. The theoretical backing for this study comes from existing research that indicates there may be a relationship between safety and quality. Although these studies provide robust evidence that a relationship could exist, opinion-based data are always subject to biases and human error. An empirical study has the potential to confirm these existing findings, although it is important to know if the opinion-based data also align with previous research. If the opinion-based data were at odds with the empirical data, this would have important implications for interpreting the findings of previous studies. Thus, the opinions of project managers on these projects were important to validate and support the empirical findings. Specifically, project managers were asked the following two questions: (1) Compared with the average project, what is your perception of safety on the project (risk, near misses, injuries)? and (2) Compared with the average project, what is your perception of quality on this project (amount of rework)? For safety perceptions, the following scale was used:

- Far worse than average (>20% more injuries/risk);
- Worse than average (10–19% more injuries/risk);
- Slightly below average (1–9% more injuries/risk);
- Average;
- Slightly above average (1–9% fewer injuries/risk);
- Better than average (10–19% fewer injuries/risk); and
- Far better than average (>20% fewer injuries/risk).

A similar scale was implemented for quality perception responses. The only difference was that the scale referred to rework instead of injuries/risk (e.g., Far worse than average >20% more rework).

Explanatory and Observational Data

As will be shown in the results and analyses, the hypothesis that there was no empirical relationship between safety and quality performance was proven false, confirming theory in literature. To explain why this relationship existed in the sample, the authors conducted semistructured interviews with project managers. On the

Table 3. Summary of Safety and Quality Metrics Data

Descriptive statistic	INJ1	INJ2	Q1	Q2	Q3	Q4	Q5	Q6
n	9	18	15	16	19	20	20	22
Mean	2.246	16.188	1.036	64.661	$4,956.39	$210,685.44	105.368	2,906.936
Standard deviation	1.666	15.338	0.981	113.499	$4,765.73	$261,526.35	246.280	5,123.657
Range	5.213	41.570	3.980	467.920	$16,510.35	$940,020.77	1,106.690	18,566.870
Minimum	0.357	0.290	0.160	2.670	$156.32	$1,155.70	2.010	66.670
Maximum	5.570	41.860	4.140	470.590	$16,666.67	$941,176.47	1,108.700	18,633.540

Note: Please see text for definitions of acronyms.

Table 4. Summary of Hypothesis Development

Hypothesis	Null hypothesis	Alternative hypothesis	Dependent variables	Independent variables
H1	There is no relationship between rework and safety	There is a relationship between rework and safety	Q3, Q4, Q5, Q6	INJ1, INJ2
H2	There is no relationship between defects and safety	There is a relationship between defects and safety	Q1, Q2	INJ1, INJ3

basis of their specific experiences on the case project, they were asked to:

1. Describe the relationship between quality performance (rework) and safety performance;
2. Describe construction management strategies that improve quality and safety performance; and
3. Describe the characteristics of a work crew that lead to strong quality and safety performance.

Results and Analyses

Separate analyses were conducted for each data set. The empirical data were compared with the opinion-based data, and the observational responses were analyzed to explain the statistical findings.

Empirical Data and Analyses

As previously indicated, the primary objective was to test the hypothesis that there is no relationship between quality performance and safety performance. The empirical data was tested for correlations between the aforementioned two safety performance metrics and six quality performance metrics. To ensure a representative comparison, the authors removed values of zero from the first-aid and rework data and searched for and removed outliers using Cook's distance (i.e., values with high leverage against the regression) as suggested by Ramsey and Schafer (2002). This action reduced the sample size to 18 projects.

Once the data were finalized, simple linear regressions were performed among the combinations of safety and quality metrics using quality metrics as predictors for the safety performance metrics. Because the predictor variables are correlated and interdependent, it was not appropriate to conduct a factor analysis or multiple linear regressions. The Pearson product moment correlation coefficient (Pearson-r) was calculated to determine the magnitude of the relationship. The Pearson-r can range in value from -1 to $+1$, with a zero representing no correlation. The larger the Pearson-r value is for the relationship, the stronger the relationship. Next, the coefficient of determination (r^2), which provides the strength of the linear correlation, was calculated. This measures the proportion of variance in one metric that is explained by the variation in the other metric, given a linear relationship. It was considered that coefficient of determination values greater than 0.50 were significant because the mathematical model explains over half of the variability in the response variable. Finally, the associated p-values in the correlation analysis were calculated. Even though there were multiple potential predictor and response variables, multicolinearity analyses were not conducted, because all predictor variables were measures of quality and all response variables were measures of safety. Table 5 shows the results of the analysis performed.

Keeping with scientific convention, the null hypothesis for each comparison was that there was no relationship between the predictor and response variables. Mathematically, no relationship would mean that the Pearson-r is equal to zero. The authors selected an alpha of 0.05, to give a standard 95% confidence interval, and performed a two tailed test. With this analysis, any p-values less than 0.05 would result in rejection of the null hypothesis and the conclusion that a relationship does exist between the two measures. The analysis returned four statistically significant relationships with p-values less than 0.05 that warranted deeper exploration.

Table 5. Summary of Empirical Data Analysis

Comparison	Pearson-r (r)	Coefficient of determination (r^2)	p-value ($\alpha = 0.05$)
INJ1 versus Q1	−0.551	0.304	0.449
INJ1 versus Q2	−0.511	0.261	0.489
INJ1 versus Q3	0.536	0.288	0.352
INJ1 versus Q4	0.358	0.128	0.554
INJ1 versus Q5	0.968	0.937	0.032
INJ1 versus Q6	0.989	0.977	0.011
INJ2 versus Q1	0.740	0.548	0.009
INJ2 versus Q2	0.850	0.722	0.001
INJ2 versus Q3	0.322	0.104	0.284
INJ2 versus Q4	0.242	0.058	0.426
INJ2 versus Q5	0.445	0.198	0.111
INJ2 versus Q6	0.181	0.033	0.535

Note: please see text for definition of acronyms.

Relationship 1: INJ1 versus Q5

A positive linear relationship was found, with an r^2 value of 0.937, between the recordable injury rate per 200,000 worker hours (INJ1) and the number of worker-hours related to rework per $1 million scope of project completed (Q5). This can be observed in Fig. 1. This means a very strong positive relationship exists. As the number of rework hours increases, the recordable injury rate linearly increases. Further, the associated p-value is 0.032, so the null hypothesis was rejected. The sample size used to make this inference was small and, consequently, the data should be considered suggestive rather than conclusive. Future research is suggested for validation.

Relationship 2: INJ1 versus Q6

Next the relationship between the recordable injury rate per 200,000 worker-hours (INJ1) and the number of worker-hours related to rework per 200,000 worker-hours (Q6) was studied. The resulting R^2-value is 0.977 indicating a very strong relationship, as shown in Fig. 2. Because the p-value is 0.011, the null hypothesis was rejected. Practically, this is the same conclusion reached in the previous relationship. Additionally, because of the same sample size limitations, this inference is suggestive only.

Relationship 3: INJ2 versus Q1

In the correlation shown in Fig. 1, a positive relationship was found between the first-aid rate per 200,000 worker-hours (INJ2) and the number of defects per $1 million project scope completed (Q1). The r^2 value of 0.548 represents a strong relationship between these two metrics, meaning as the number of defects on a project increases, the number of first-aid injuries also increases, as depicted in Fig. 3. The associated p-value 0.009 led to a rejection of the null hypothesis.

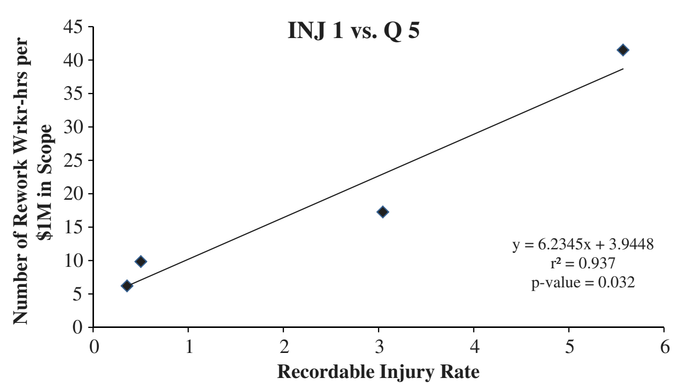

Fig. 1. Recordable injury rate per 200,000 worker-hours (INJ1) versus the number of worker-hours related to rework per $1 million of scope of project completed (Q5)

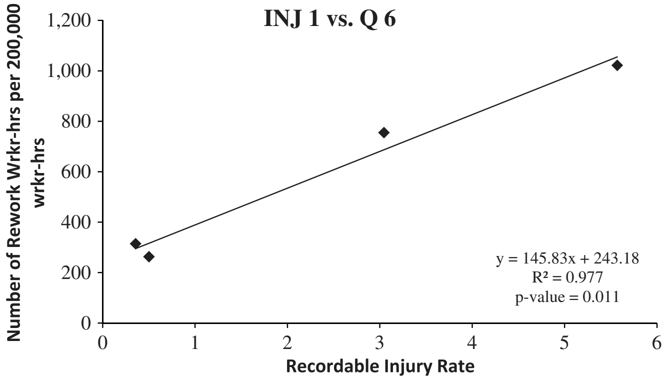

Fig. 2. Recordable injury rate per 200,000 worker-hours (INJ1) versus the number of worker-hours related to rework per 200,000 worker-hours (Q6)

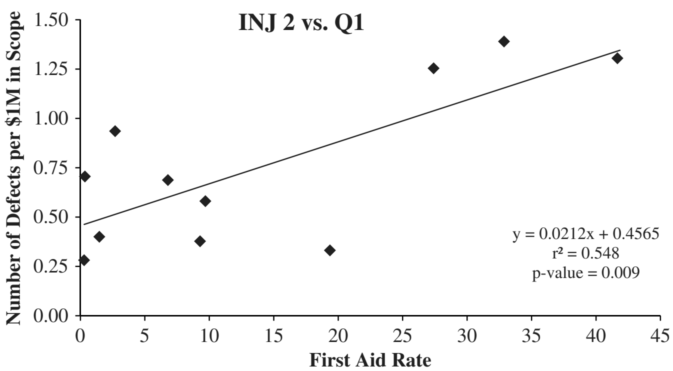

Fig. 3. First aid rate per 200,000 worker-hours (INJ2) versus the number of defects per $1 million project scope completed (Q1)

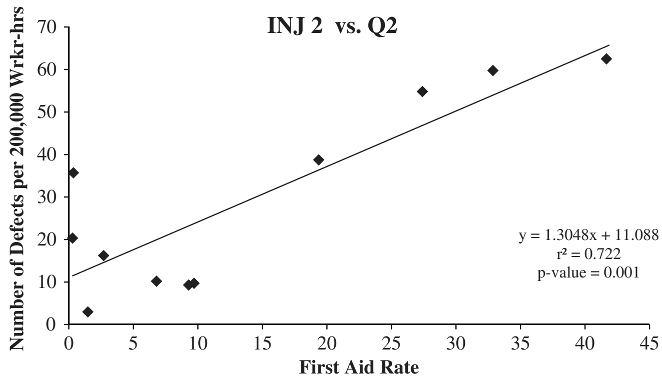

Fig. 4. First aid rate per 200,000 worker-hours (INJ2) versus the number of defects per 200,000 worker-hours (Q2)

Relationship 4: INJ2 versus Q2

The final realized relationship shown in Fig. 4 is similar to the previous in that a positive correlation exists between first-aid rate per 200,000 worker-hours (INJ1) and the number of defects per 200,000 worker-hours (Q2). Again, this infers that, as the number of defects increases on a project, the first-aid rate increases as well. The r^2 value of 0.722 indicates that a strong relationship exists, and the p-value <0.0011 led to rejection of the null hypothesis.

Opinion-Based Data and Analysis

When analyzing the opinion-based data, the data provided from 28 project managers was included. Because the categories are not evenly divided, they are considered nominal and cannot be treated like continuous data. Hence, the responses were ranked from 1 [Far worse than average (>20% more injuries/risk)] to 7 [Far better than average (>20% fewer injuries/risk)], and the Spearman rank order test was conducted. The Spearman rank-order correlation coefficient (Spearman-r) is a measure of association between two variables measured on an ordinal scale. The p-values indicate whether or not to accept the null hypothesis that there is no correlation. Having p-values close to zero indicates a high level of confidence that the null hypothesis is incorrect. That means that a p-value of less than 0.05 indicates a correlation between two values categories. The Spearman-r correlation results show that there is a relationship between the overall perception of safety and quality on a project. The less rework performed, the lower the probability of injuries or risks.

Open-Ended Interview Responses

The final analysis reviewed the responses to the open-ended questions to understand why the relationship between quality and safety exists and to understand the management strategies that promote the achievement of both. The responses provided in this article are individual comments, and not all of the collected comments have been included. However, the provided comments represent the majority of responses for a particular topic.

Perhaps the most enlightening quote from a project manager is as follows: "I firmly believe that there is a direct relationship between rework and safety performance. Four years ago, (we) started looking at the root causes of the recordable injuries within (our company). We found that over 60% of all our injuries were in the performance of rework. Over the past four years as we have improved the quality of our projects, we have had a corresponding reduction in recordable injuries."

Another contractor confirmed these ideas, and elaborated on why more injuries occur during rework activities, stating that, "National statistics [state that] 60% of injuries occur during rework. This means that workers who are redoing work are focused on trying to get it done and providing the quality needed, but are not so much concerned with safety practices." Indeed, rework often occurs under intense schedule pressure, and a number of project managers cited time as being a major driver of both quality and safety. One contractor elaborated on this, saying, "Quality goes along with not taking shortcuts, safety comes hand in hand; I think it starts with putting guys in the right place at the right time and giving them the right duration to finish what they do." It follows, therefore, that rework would create time-limited situations that emphasize schedule compliance over safety. This creates conditions in which injuries are more likely to occur. Another project manager cited a different reason for the high incidence of injuries during rework, stating that: "Another reason of risky situations, rework orders are due to field work by hand." [Rework orders are performed in the field, usually by hand. This generates hazardous situations for workers.]

Not all project managers agreed with these conclusions, however, and out of the 24 open-ended responses, only three mentioned that they did not believe there was a direct relationship between safety and quality. One of these project managers said, "I personally don't feel these are directly related. You can have a very safe project but have poor quality and/or a lot of rework and vice versa." The project manager went on to say that both safety and quality can be improved through selective subcontractor hiring, which implicitly indicated that they have similar causal factors. The main argument was that safety and quality do not intrinsically have a relationship, and ultimately they can vary independently. One contractor stated, "[I] do not believe there is a direct relationship between the two. Both [safety and quality] deal with management's attitudes and employee's concern for personnel safety and ownership/pride in their work."

Once again the contractor cites common underlying factors that affect both safety and quality, but does not believe that they are directly related. Another way of expressing this point would be that decreased rework does not cause increased safety performance, and that increased safety performance does not necessarily cause decreased rework. Previous quotes directly challenged these dissenting opinions by implying a causal relationship between rework reduction and increased safety performance. It is important to recognize that there are multiple viewpoints.

Interviewees identified a number of reasons why the authors may have observed the empirical relationships, and most identified linking factors that affect both injury rates and quantity of rework. These themes are important from a management perspective because strategies to mitigate these factors will promote better safety and quality performance. One emerging theme was the importance of allowing adequate time for successful construction execution. During preplanning, it is essential for the contractor to make realistic scheduling estimates. As one project manager said, "if a contractor is given the time to perform in a quality manner, rework goes down and safety is better." It would seem that time is a linking factor that mutually affects safety and quality. In fact, limited schedules can lead workers to do poor work, because, "quality goes along with not taking shortcuts, [and] safety goes hand in hand." When workers are put on severe time crunches, they are more liable to take shortcuts and make mistakes.

Another pervading theme was the importance of multiple levels of leadership. On one hand, safety and quality comes from top-down leadership such that "Learning best practices, lessons learned on future projects, early involvement, however how early is not up to the CM/GC as that falls on the owner." Other times, however, project managers placed a heavy emphasis on the importance of localized work crew leadership. One contractor stated that it was essential to "have a good leader on the crew that really cares about safety and quality." On work crews, safety and quality are dependent on having "strong leadership from their foreman [who] has full authority to act on behalf of their company at the lowest level." Thus, empowering leadership and encouraging accountability to lower levels of leadership is also important to foster both safety and quality.

Another strong theme focused on the importance of preplanning on multiple levels in reducing injuries and increasing quality. As one project manager claimed, "Preplanning is the absolute key; more planning on the front end means a better chance of quality and safety that the project can achieve." Similarly, contractors placed a very high value on having work crews that were informed and prepared, so that they are not making decisions on the fly while in the field. As far as subcontractor planning goes, "the more detail the better. It shows that they've prepared their work and know what they need to do." Furthermore, processes that are unknown were cited to decrease quality and safety by increasing mistakes. One project manager aptly stated that "it comes down to known processes versus unknown means and methods; the more you get guys out of the comfort zone they are more likely to make mistakes, forcing them into a learning curve they would not otherwise go through." Because designers do not often design for safety or quality, preplanning becomes even more important to familiarize unknown means and methods.

One management strategy that was mentioned several times was finding quality workers and encouraging them to have pride in their work through trust and accountability. Project managers emphasized the importance of "assembling a team of subcontractors that have proven themselves as safe and quality oriented; after you get guys like that under contract, be thorough with the submittals process and shake out details." After hiring good people, "making our craftsmen and foremen accountable for safety and quality is the first step. We expect and empower our team members to stop work if they think it is unsafe. We also expect them to stop work if work is being installed incorrectly or in a manner that does not meet the contract drawings and specifications." In fact, treating subcontractors and workers with respect may be an excellent way to encourage good work practice. This sentiment was reflected by one project manager, who stated that "For the most part people take pride in their work; if their standard of work is poor it reflects on them as a person. Meaning they are more than likely have the same poor standards in regard to safety." Thus, encouraging subcontractors and workers to have pride in their work may increase both safety and quality.

Study Limitations

The authors recognize the following limitations of the study that adversely affect the internal validity, external validity, and reliability:

- A relatively small sample size that limits the ability to generalize the results to the entire construction industry. A major reason that the sample size was small was the reluctance of the contractors to provide sensitive data. The authors recommend further study with a larger number of projects to address this limitation.
- This data set had some missing data because some contractors do not measure or track all values requested. Most commonly, first-aid injuries and the number of items requiring rework were the least-tracked data, whereas OSHA recordable injury rates and the dollar value of rework were the most-tracked data.
- A disproportionate proportion of projects (47%) were located in Colorado where the study was conducted. This limitation reduces the ability to generalize the results to other states. However, there is no reason to believe that Colorado is a special population. Thus, it is reasonable to believe that the results can be generalized.
- This research does not consider other safety interventions implemented by the contractor or the quality of their safety program.
- The size of projects varied widely, which may limit the ability to generalize the findings to a particular portion of the construction industry.
- The sample size used to examine some specific relationships (i.e., Figs. 1 and 2) are very small and, thus, should be considered suggestive only and as prompts for future inquiry.

Conclusions

The research objective was to empirically examine the relationship between construction quality and safety performance for the first time. Data from 32 construction projects of varying size, scope, and location were collected to meet this objective. On the basis of the empirical and opinion-based data analysis, it is evident that there is a correlation between construction safety performance and construction quality. The empirical data suggest two relationships that support this finding: the recordable injury rate is positively correlated to rework, and the first-aid rate is positively correlated to number of defects. The authors conclude that a project with a poor quality performance has a higher likelihood of injuries. The opinion-based data support this finding, showing that there is a relationship between perceived safety on a project and perceived construction quality. Finally, qualitative interview data were used to discover more specifically why a relationship exists and possible management approaches to simultaneous improvement of safety and quality.

The empirical findings fill a significant gap in the existing literature by using project-based data to explain the relationship between quality and safety. Although existing literature used opinion-based data to anecdotally establish a relationship (Hatush and Skitmore 1997; Hoonakker et al. 2010), previous research had not mathematically modeled the interaction between quality and safety. Because the empirical findings were supported by the opinion-based data, this work supports the existing body of knowledge and validates previous qualitative studies. Effectively, the authors repeated the qualitative opinion-based portion of other studies and concluded that their findings were accurate and repeatable and that there was a theoretical relationship between quality and safety. This combination of empirical and opinion-based data provides a firm base on which to build future studies. Although safety is a desirable outcome by itself, companies must balance safety investments with a number of other business decisions. On a strategic level, this study reveals that safety and quality are related on construction projects, and that there are management strategies that can jointly improve safety and quality performance. This is important because it allows better allocation of resources and links an outcome desired by owners (quality) to a liability held by contractors (safety). Furthermore, a number of useful management strategies have been identified that simultaneously improve safety and quality. These include devoting resources to preplanning, dedicating the necessary time to complete tasks well during estimating, encouraging leadership on a crew level, and encouraging workers to take pride in their work by holding them accountable for their responsibilities.

Linking safety to quality provides the academic field with a more holistic pathway to encouraging safety improvements. Some researchers have taken a more holistic perspective, examining how total quality management (TQM) can lead to simultaneous improvement of both safety and quality. With this approach, researchers can begin to explore construction safety in terms of the confounding factors and complexity that are inherent in an actual worksite.

Future studies can build on this research paradigm in a number of ways. First, the extant literature has yet to relate safety to other confounding factors on construction sites. For instance, simple building practices versus complex construction may positively or negatively impact safety performance and strengthen the argument that one should design for safety. Similarly, the project delivery method may affect safety on a project, but current studies provide no empirical evidence. It is important for future research to empirically relate safety to other factors on construction sites to provide added incentive to drive safety forward.

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