Construction Management and Economics (April 2011) **29**, 341–353

Routledge
Taylor & Francis Group

Fatigue: the most critical accident risk in oil and gas construction

MARGARET CHAN*

School of Civil Engineering, The University of Sydney, Sydney, NSW 2006, Australia

Received 17 December 2009; accepted 4 December 2010

Construction work in oil and gas projects is both challenging and hazardous. The occupational hazards are often associated with fatigue and stress, and an accident is one possible outcome. The purpose of the two-part study was to identify the new and emergent risks within the top 10 ranked risks and to evaluate their contribution to accidents. Three hundred and twenty stakeholders, from four oil and gas construction projects in mainland China participated in the survey questionnaire. Fifteen workers, who have experienced actual fatigue-related accidents, were also interviewed. All of the stakeholders unanimously ranked fatigue as the most critical risk perceived to cause accidents with emotional disturbance, the emergent risk. This is the first time that fatigue has been identified as the leading accident risk in the construction industry. It was further reported as a trigger risk to a bundle of other synergetic risks. The new discovery confirms the need to consider fatigue as a complex multidimensional phenomenon and the lynchpin to reducing accidents. These findings have created new responses to the problem of accident causation and alternative views to accident mitigation. The discoveries will open new opportunities for future research in the areas of fatigue and stress risk management in construction.

Keywords: Accident, China, fatigue, gas construction, oil construction.

Introduction

Working in oil and gas construction projects is both challenging and hazardous due to the remote and hostile work environment and the demanding shiftwork schedules, which often necessitate daily adaptation. These occupational hazards are often associated with fatigue and stress-related risk factors and accidents are a possible outcome. Research has highlighted the importance of the early detection of critical risk factors so that accidents can be mitigated or averted in the first instance.

Despite a plethora of studies on safety management in the construction industry, critical accident risks pertinent to the oil and gas industry have hitherto not been well understood or researched. Indeed, safety factors were thoroughly investigated in building construction projects from across the globe. Some examples include studies by Kheni *et al.* (2008) in Ghana, Koehn and Reddy (1999) in India and Aksorn and Hadikusumo (2008) in Thailand. However, these studies though insightful are not pertinent to the oil and gas construction industry. Critical risks in offshore and onshore oil and gas construction differ significantly from building construction, as the 'risk picture' is different. Of particular concern are the oil and gas accidents, which are usually a 'one off', but could have far-reaching repercussions such as the recent BP oil rig explosion in the Gulf of Mexico.[1] Hence, according to Anderson and Lagerlof (1983) any attempt to understand an accident is often aligned with the search for its root causes.

The purpose of this two-part study was to develop a list of top 10 ranked critical accident risk items from the perspective of different and culturally diverse groups of internal stakeholders, whose views are pivotal in achieving their organizational health and safety (HS) goals. The accident risk management issues were investigated through exploring human and organizational factors that contribute to accidents by addressing the following research questions: (1) What are the top 10 ranked critical accident risks? (2) Which are the new

*E-mail: margaret.chan@usyd.edu.au

Construction Management and Economics
ISSN 0144-6193 print/ISSN 1466-433X online © 2011 Taylor & Francis
http://www.informaworld.com
DOI: 10.1080/01446193.2010.545993

and the emergent risk items? (3) Do the perceptions of the different internal project stakeholders converge or diverge? (4) What are the risks (antecedents and exogenous risks) that are associated with fatigue in mediating and mitigating site accidents?

Overview of the current knowledge on accident risk management

The current state of knowledge encapsulating recent developments in the field of accident risk management will now be reviewed. It will highlight the current limit to the body of knowledge and demonstrate that the 'gap' including the research questions have not been adequately addressed.

Accident risk management

A study by Pate-Cornell and Murphy (1996) has shown that a large proportion of site accidents were management-related. According to Zhou (2007) construction accidents can cause injuries, illness and even fatalities, usually due to inadequate or lack of management commitment and control over safety practices. Since effective safety management is dependent on how risk is perceived and assessed, and how coherent are the decisions that are made to control the risks, the search for risk factors has intensified over the years.

Among numerous methods advocated for improving safety at the construction site, the concept of risk management has gained prominence over the years. Consistent with the view of Tweeddale (2003), the term 'risk management' encompasses identifying and assessing risks associated with site accidents, as well as setting goals and developing appropriate operating systems for their control. Jackson and Loomis (2002) advocate that by identifying and analysing critical risk factors, appropriate managerial action can be taken to mitigate or avert accidents, thereby avoiding fatality.

A popular and useful method for identifying risk factors is the use of a safety audit checklist. It is also one of the most useful tools for hazard identification. According to Khan and Abbasi (1998) one of the advantages of this method is to ensure that some of the risk factors are not overlooked. Hence, a relevant, comprehensive and authoritative list of critical risk factors that is industry specific is crucial so that risk factors can be classified in a structured and meaningful framework for the development of appropriate safety intervention strategies. However, one of the daunting challenges facing expatriate HS managers of mega Sino-joint venture oil and gas construction projects, who are usually the key drivers of HS initiatives, is the lack of relevant published checklists of critical risk factors to assist them to combat the nature and types of risk typically faced by the indigenous workforce. This is crucial because according to Hsu *et al.* (2008) checklists should be culturally relevant so that managers could take prudent measures to assess, rank and manage these risks in the context of the culture of the country in which the accidents occurred. Hence, the development of a relevant and culturally appropriate checklist is warranted.

In addition, prior studies by McLain and Jarrell (2007) and Cox and Tait (1998) have also shown that there is a difference in risk perception between project stakeholders, and this difference would provide a means for transcending the mono-cultural view of the West which currently dominates the scientific literature. Furthermore, there is currently a lack of knowledge regarding the relative importance of different risk factors in this sector. Prior studies by Tam *et al.* (2004) and Zeng *et al.* (2008) on the ranking of accident risk using non-standardization of methodology from the study makes comparison problematic. Therefore, in the absence of epidemiological studies and research, it can be argued that no updated, relevant and comprehensive list existed in this area of study. Hence, an investigation into the critical risks pertinent to this industry and their role in accident causation warrants further interrogation.

Risk factors contributing to accidents

According to Rowlinson (1997) an accident is defined as an unplanned incident leading to death, injury or property damage, which stems from inadequate management control of work processes, manifesting itself in personal or job factors that lead to substantial actions or conditions seen as immediate causes of the accident. However, according to Petersen (1975), the underlying root causes of accidents are multiple, not just unsafe practices or work conditions, which are symptoms of the problem, and many causes may contribute to an accident. For example, unsafe work conditions are symptoms of management oversight and lack of control, which can lead to a lowering of performance standards and subsequently to a chain of tragic events. Liska *et al.* (1993) are of the opinion that the consequence of inadequate management control allows the existence of four groups of factors such as personal and job factors, unsafe work conditions and unsafe practices to contribute to accidents. Indeed, studies in the UK by Gyi *et al.* (1999) and Donaghy (2009) have demonstrated that top management (e.g. directors) involvement in HS management, including individual construction workers' attitude to unsafe practice and the use of unsafe equipment are some examples of accident causal factors.

While the four groups of risk factors and their individual roles in accident causality have been well researched, little is known of how various risk items within each group interact with each other to bring about an accident in the oil and gas construction projects. For example, in a study built on multi-causality of accidents by Reason (1990), Haslam *et al.* (2005) constructed a complex model to explain how accidents arise from a failure in the interaction between the work team, workplace, equipment and materials to give rise to the 'immediate accident circumstances'. While the model is thought provoking and very relevant to the construction industry in general, the multi-causality of accidents specific to oil and gas construction projects have, to date not been researched and further exploration is required.

Human error and fatigue

Despite the identified 'gap' in the knowledge, one well-established fact is that among the phenomena that lead to accidents, human error is the most unpredictable. According to DiMattia *et al.* (2005), ignorance of hazards present and lack of proper training were often risk factors behind human error while exposure to hazards such as fire as identified by Gyi *et al.* (1998) compounded the problem further. Reason (1990) is of the opinion that even well-trained people occasionally make such errors, and one must either accept an occasional mistake or change the work situation to minimize or remove opportunities for error. However, studies by Folkard and Tucker (2003) have indicated that human error as a result of fatigue is the most dangerous. Lamond and Dawson (1999) argued that fatigue could result in performance impairment equivalent to, or greater than 0.1% of blood alcohol concentration (BAC)—a level that is deemed unacceptable for driving a crane, or operating dangerous equipment. It is also four times more likely to contribute to workplace accidents than drugs or alcohol. An example of accident associated with fatigue is the grounding of Exxon Valdez on Bligh Reef in Alaska on 24 March 1989. Despite the danger of fatigue, its critical role in accident causality in construction has until now been overlooked.

Although 'tiredness' has been reported as a construction accident risk by several studies, less attention was paid to this risk. For example, a study in mainland China by Cheng *et al.* (2004) has relegated 'tiredness of workers due to overtime duties' to the ninth position out of 14 factors affecting site safety. Similarly, a study in Malaysia by Hamid *et al.* (2008) ranked fatigue as fifth out of 9 accident causal factors; however, in that study fatigue was associated with overexertion or strenuous movement. Similarly, workers' health and fatigue was relegated to the last position out of 21 accident causal factors by Haslam *et al.* (2005).

Indeed, studies by Barofsky and Legro (1991) have indicated that fatigue is more than mere tiredness or overexertion and although it is one of the outcomes of excessive overtime work, it is a far more complex phenomenon. Folkard and Tucker (2003) considered fatigue as a multidimensional phenomenon, encompassing physical, mental and emotional stress and other behavioural aspects, all of which require further exploration if the breadth of the experience of fatigue is to be understood. Indeed, apart from physical strain, one's mental or emotional state can cause distraction leading to accidents. In Hinze's (1996) theory of distraction, he argued that factors such as time pressure to complete projects and one's mental state can distract the workforce from hazards and this increases the probability of accidents. Similarly, the 'constraints-response' theory by Suraji *et al.* (2001) further supports the argument that project conditions, management decisions or emotional distress (dismal factors) can cause responses that create inappropriate actions (proximal factors) thus leading to accidents. A study by Gyi *et al.* (1999) also considered behavioural issues such as failure of individual workers to follow safety rules as an important accident risk factor. The finding was corroborated in a study by Haslam *et al.* (2005) in that one of the reasons why safety was being compromised was due to the workers' heavy workloads and other priorities. Hence, the multi-phenomenal aspect of fatigue has been under-researched in oil and gas construction management and the research area warrants further attention.

Fatigue and its associated risks

While fatigue as a single risk factor has been thoroughly investigated in Western literature, its association with a group of other stress-related risk factors in the oil and gas construction industry have hitherto remained relatively unexplored. For example, failure to use personal protective equipment (PPE) due to inadequate communication between the supervisor and a fatigue worker could put him at a high risk particularly when he is working in an environment involving fire or explosion. According to a study by Sui (2001), working in unsafe work conditions not only increases the mental stress of a worker but also exposes him to a higher risk of accident if he is fatigued as he may suffer from momentary performance lapse. Several studies by Folkard and Tucker (2003) and Nachreiner (2000) have shown that a fatigued shift worker's level of alertness is constantly fluctuating and the probability of an accident occurring rises and falls with the level of his alertness with the poorest job performance consistently occurring on the night shifts. Hence, fatigue and its synergetic group of associated risks are inextricably intertwined with each other and their tenuous connection warrants further exploration.

Methods

The sample

A sample of 320 internal stakeholders, recruited by stratified random sampling method was selected from a workforce of 45 500 within the participating project sites. These comprised 253 (79%) Chinese migrant workers, 44 (13.8%) Chinese safety supervisors and 23 (7.2%) managers.[2] There was unprecedented access to four high profile projects, which included the construction of two of the world's largest Sino-joint venture ethylene cracker complexes (BP SECCO[3] project in Shanghai and Shell CSPC[4] project in Huizhou). The third was China's first Sino-joint venture liquefied natural gas (LNG) receiving terminal and pipeline (Guangdong LNG[5] project in Dapeng) and one foreign project (BP liquefied petroleum gas project in Zuhai).

Participants' characteristics

In the sample, the mean age of the respondents was 29.5 years old, the highest formal education was nine years and the maximum length of work experience was more than six years. Seventy-eight per cent or 226[6] respondents nominated fatigue as a critical risk perceived to cause accidents. Eighty per cent of these respondents worked more than eight hours a day, 63% on double shifts, and 91% on weekends and public holidays.

Furthermore, the majority (61.7%) of these respondents were in the age group of 26–30 years old, compared to 1.9% who were above 40 years old. Fifteen migrant workers who experienced actual fatigued-related accidents were also drawn from the sample for further analysis.

Materials

The empirical data in the two-part study were collected using quantitative and qualitative methods. The merit of this 'balanced' approach was advocated by Parkhe (1993) in that this method not only allows previous theory to inform, but also does not inhibit theory development. Hence, to answer the first three research questions in the first part of the study, a survey instrument, which comprised a self-reported questionnaire (English questionnaire for the expatriates and Mandarin for the indigenous Chinese workforce) was developed. To ensure consistency, validity and reliability in the two versions of the questionnaires, different but consistent typefaces were used and questions were numbered consistently to aid translation, understanding of branching instructions, editing, encoding and tabulating of the responses. Three hundred and fifty questionnaires were distributed across four sites but only 320 (91%) were usable replies. The effective response rate was 97%.

The questionnaire utilized three key components (Sections I–III): Section I comprised questions related to the respondents' work history, while Section II (immediate cause of accidents) comprised 10 questions (72 multiple-response answers) and Section III (system cause of accidents) comprised 14 questions (147 multiple-response answers). Altogether the participants were asked to select from a total of 219 randomized multiple response (yes/no) answers within the 24 questions, the risk items they perceived to cause accidents at their worksite (Figure 1).

The 219 risk items were compiled by the author based on a literature review and from the oil and gas accident taxonomy chart that was used at the four participating sites.

To answer the fourth research question in the second part of the study, a data mining analysis was performed on 226 responses. The purpose was to deepen the study to investigate the relationship between fatigue and its associated risk and the explanatory power of these risk items. In order to triangulate and augment the results from the analysis, semi-structured interviews were subsequently conducted on 15 respondents (Chinese migrant workers) who had experienced actual fatigue-related accidents.

Data analysis procedure

To answer the research questions in the first part of the study, the Software Package for Social Science (SPSS) version 15 was utilized to perform the cross-tabulation analysis and the chi-squared test. In order to derive a ranked list of risk items to answer the first research question, the initial phase of the procedure was to encode the participants' binary responses to the questions (Sections II and III) with 1 = yes if they chose a particular risk item or 0 = no if they did not choose that risk item. Subsequently, the responses, which were coded one, were aggregated together based on cross-tabulation frequency count. The risk item with the highest frequency count (percentage) would be ranked first and considered the most critical risk item and vice versa. A chi-squared test was performed on the dataset to assess whether the views of the three groups of stakeholders converged or diverged.

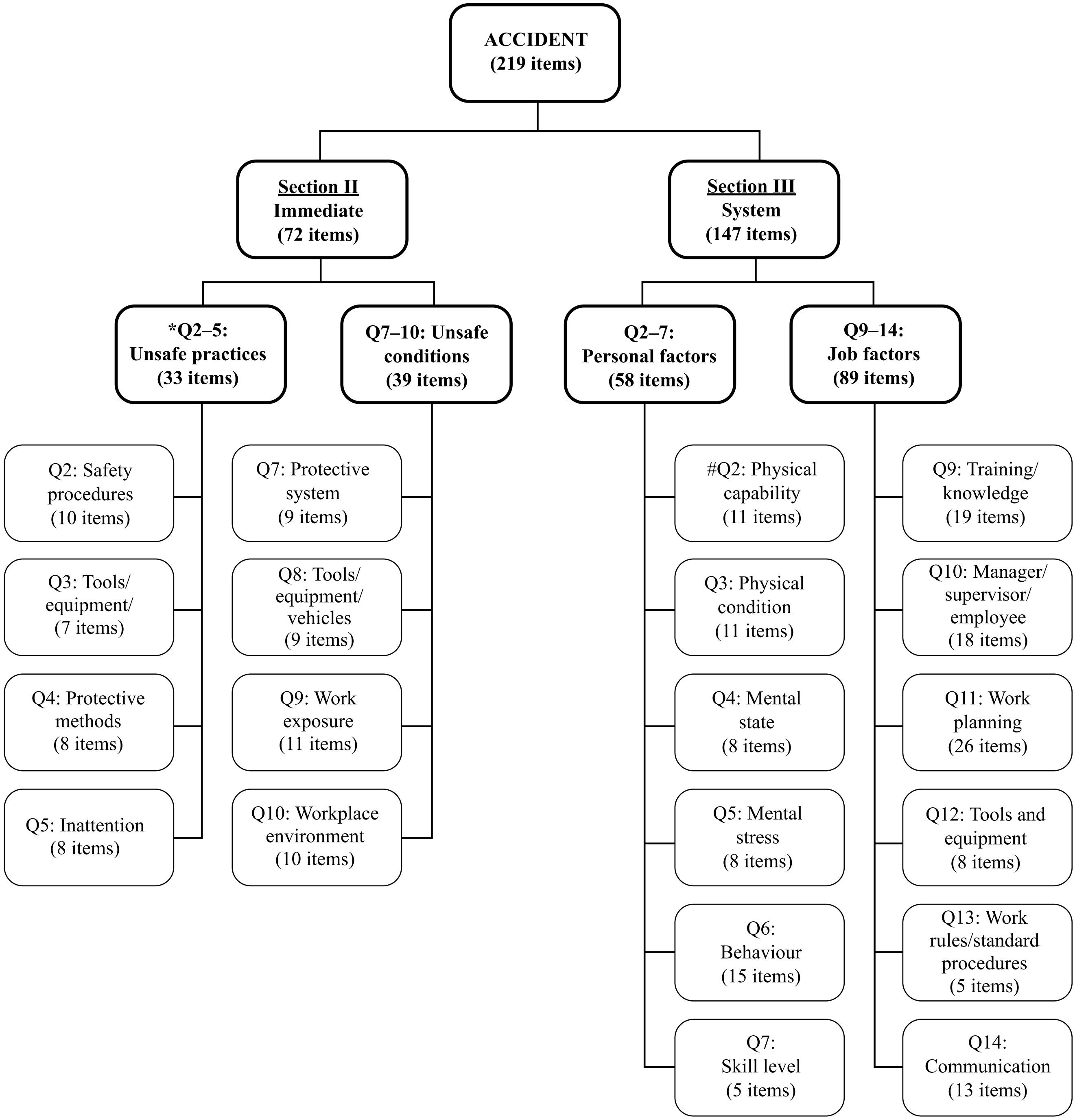

Figure 1 Summary of number of risk items within accident taxonomy
Notes: *Q represents the question number in the questionnaire and the brackets ( ) refer to the number of risk items in those questions that the respondents had to select. Questions 1, 6 in Section II, and 1 and 8 in Section III are branching questions pertinent to unsafe practices, unsafe work conditions, personal and job factors, respectively.
#Fatigue is one of the 11 multiple response answers under physical capability in Q2 Section III.

In the second part of the study, SPSS Clementine Version 15 software was used for the data mining for association rule analysis. This exploratory technique was used to detect meaningful but 'hidden' knowledge as well as underlying structure in the data that might be overlooked using conventional statistical techniques (Delmater and Hancock, 2001). SPSS Version 15 was used for the chi-squared and correlation test while NVivo 2 software was used for the qualitative analysis. As the data mining analysis is a novel technique (based on the *a priori* association rule strategy by Agrawal and Srikant (1994)) very rarely utilized in the construction industry, a brief description is provided. The data mining analysis is used to uncover 'interesting' relationships between the 218 risk items or antecedents (denoted by *B*) and fatigue, the most critical risk or consequent (denoted by *A*).

The analysis begins by first 'mining' for antecedents that concur synchronously with the consequent. For example, when a respondent selects fatigue as the accident risk item perceived to cause accident, what other associated risk items did he also select? In the study, the minimum support threshold was set at ≥ 10% and the minimum confidence level ≥ 30%; thus any combination of the association rules satisfying this standard are known as 'interesting' items. Furthermore, 'lift'[7] which is a correlation analysis was used to augment the support-confidence framework. Nine hundred association rules were generated; however, only 10 rules with the highest lift were presented (Table 1).

Chi-squared analysis was subsequently performed on these rules to further validate the results generated by the data mining and to verify the independence between the two identified variables (antecedents and consequent). Additional exogenous risk items correlated with the antecedents were further tested using the Spearman's correlation coefficient to investigate the relationship of these items with the antecedents and the consequent.

Results and discussion

Building on the results from the first three research questions, the key findings from the second part of the study will be drawn together to provide a plausible explanation as to the likelihood or probability of *how* and *why* accidents might occur with fatigue as the trigger risk and the lynchpin to accident mitigation.

The new and emergent risks

Although the findings in the first study ranked the 219 risk items, only the top 10 ranked critical risk items with the highest frequency were reported for discussion as they were deemed more important and worthy of management attention. These risks were subsequently

Table 1 Top 10 ranked** association rules with fatigue as the consequent

Rank	Antecedents *(A)*	Consequent *(B)*	Rule support %	Confidence %	Lift^	p-value
1	Protective methods (improper use of PPE) and tools/ equipment (improper use of equipment)	Physical condition (fatigue)	9.877	88.889	1.763	0.008*
2	Mental stress (frustration) and skill level (inadequate practice of skills)	Physical condition (fatigue)	9.465	88.462	1.755	0.017*
3	Protective methods (improper use of PPE) and work exposure (fire or explosion)	Physical condition (fatigue)	9.053	88.000	1.746	0.031*
4	Inattention, lack of awareness (distracted by other concerns) and work exposure (fire or explosion) and safety procedures (failure of individual workers to follow safety procedures)	Physical condition (fatigue)	8.848	87.755	1.741	0.005*
5	Mental state (emotional disturbances) and tools/ equipment (improper use of tools)	Physical condition (fatigue)	9.671	87.037	1.727	0.040*
6	Mental stress (frustration) and tools/ equipment/vehicles (defective equipment)	Physical condition (fatigue)	9.465	86.792	1.722	0.048*
7	Mental stress (emotional overload) and inattention or lack of awareness (distracted by other concerns)	Physical condition (fatigue)	9.465	86.792	1.722	0.048*
8	Mental state (emotional disturbances) and skill level (inadequate practice of skills)	Physical condition (fatigue)	10.700	86.667	1.719	0.015*
9	Protective methods (improper use of PPE) and protective methods (failure to use PPE) and communication (inadequate supervisor–worker communication)	Physical condition (fatigue)	9.259	86.538	1.717	0.048*
10	Protective methods (improper use of PPE) and communication (inadequate supervisor–worker communication)	Physical condition (fatigue)	9.259	86.538	1.717	0.048*

Notes: ** Ranked based on lift value. * Significance at the 0.05 level (one-tailed).

^ If lift <1, then the occurrence of *A* (fatigue) is negatively correlated with the occurrence of *B* (antecedents). If lift >1 then *A* and *B* are positively correlated.

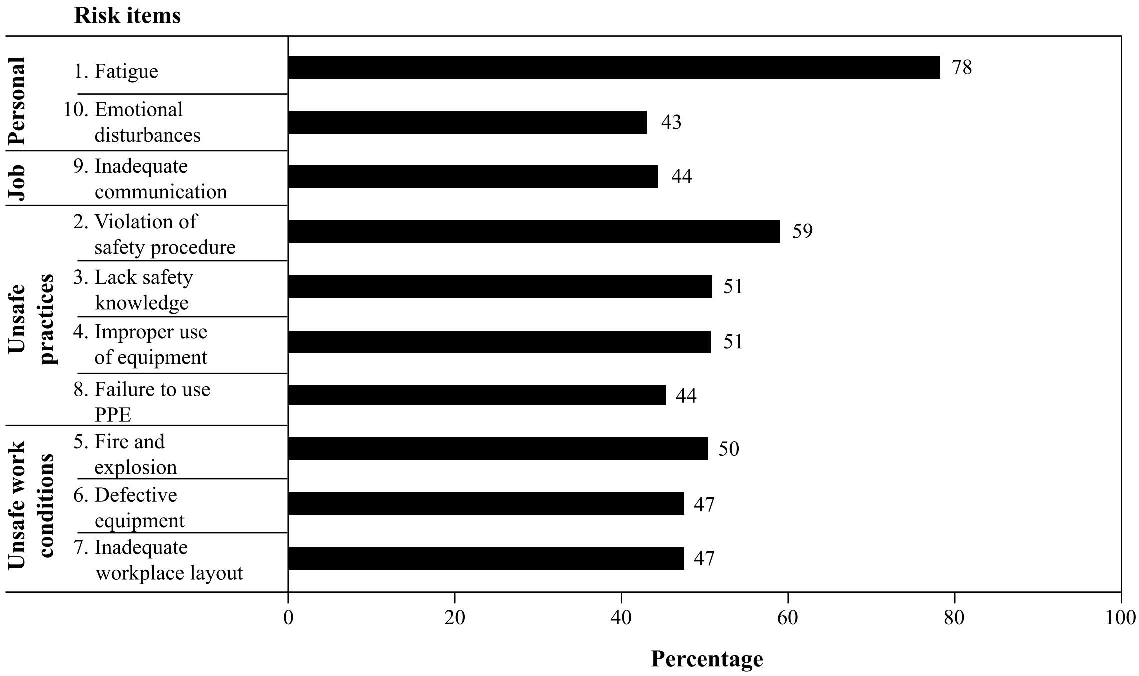

Figure 2 Ranking of top 10 critical risk items
Notes: Risk item ranked 1 = most important while risk item ranked 10 = least important. Violation of safety procedure (ranked 2nd risk item) refers to failure by individual worker to follow safety procedure.

organized into four groups by their sources into a systematic framework (Figure 2) to trace the hierarchy of risk items back to their original sources. This is imperative because unless a classification contains a particular category of interest, the information would be meaningless and retrieval difficult.

Given that mainland China is a society in transition with radical changes in the construction landscape, it is not surprising to find new and emergent risks. In the study, 78% of all stakeholders unanimously ranked fatigue[8] as *the* most critical accident risk item perceived to cause accidents. The chi-squared test further showed no significant difference in the perception of the three groups of stakeholders ($p = 0.613$) (Table 2). While fatigue has been associated with accidents in other industries (e.g. Gander *et al.*, 2000), this is the first time it has been identified as the leading accident risk in the construction industry. A previous study by Cheng *et al.* (2004) has also reported 'tiredness' as one of the risks in construction in mainland China. However, based on empirical evidence in the study, fatigue is a phenomenon far more complex than mere tiredness. This distinction will be discussed in the second part of this section. Even though emotional disturbance,[9] which is a mental state, was ranked tenth in position by all stakeholders (43%), it was nevertheless identified as an emergent risk item. This risk has also not been previously reported in this industry. Interestingly, managers deemed this risk item (ranked fourth) to be more important compared to the other stakeholders (ranked seventh by safety supervisors and tenth by workers) ($p = 0.477$) (Table 2).

In addressing the new and emerging risks, the initial findings seem to suggest that these two elements of risks have remained largely undetected and may have emerged during the last few years. They not only represent a largely unexplored area in construction risk management but also reflect the dynamic nature of this industry. The emergence of these risk items will indeed create new challenges for HS personnel in the immediate future. Given the new risks identified in the study, the key question to ask is: are these risks new? Had earlier research been conducted in a manner similar to this study, or had access been granted to the four construction sites by other researchers, it is probable that these risk items would have been discovered. However, the author argued that it is more likely that the increasing pervasiveness of extended working hours,[10] which is an industry norm in mainland China, may have desensitized HS personnel to overlook the need to exercise prudence in achieving work-life balance at their worksites.

The findings of the other eight common risk items (Figure 2) have remained relatively stable or diminished in importance. With the exception of fire or explosion, which is predominantly a major threat in the oil and gas construction industry, the other seven risk items have been thoroughly investigated in prior literature.

Fatigue as a trigger accident risk

Although fatigue has been identified as the most critical risk item, the results from the second study indicated that a single risk item is unlikely to influence the occurrence of accidents. On the contrary, accident occurrence is associated with a confluence of associated risk items that concur synchronously with fatigue as the trigger risk item. The empirical evidence from the study corroborated the multi-causality of accident theory propounded by Reason (1990).

An illustration (Association Rule 4) from Table 1 will be used to discuss how fatigue can play a critical role in triggering a bundle of synergetic risk items leading to the multi-causality of accidents. In this example, there is 87.8% confidence that the occurrence of the consequent (fatigue) is associated with accidents given the occurrence of a group of antecedents (distraction by other concerns, fire or explosion, and failure of individual workers to follow safety procedures). In other words, there is 87.8% probability that the respondents who selected these pairs of antecedents were most likely to select fatigue as a risk item perceived to cause accidents. A chi-squared test also detected a significant dependence between all the pairs of antecedents and the consequent ($p < 0.05$*) (Table 1). This test further validated the data mining results that showed that the occurrence of the antecedents is dependent on whether the respondents were fatigued or not. Furthermore, as the lift value (1.741) was both positive and strong (>1) this implied that the occurrence of the antecedents would increase or 'lift' the occurrence of the consequent and vice versa. For example, an increase in the fatigue level of a respondent would be associated with an increase in his failure to follow safety procedures in combination with an increase in his distraction if he is working in a place exposed to fire or explosion (Figure 3). Conversely, if the fire or explosion at his workplace decreases, so would his failure to follow safety procedures and his distraction decrease. Similarly, the decrease of the three antecedents combined together would be associated with a decrease in fatigue.

This data mining result was further triangulated in a sample interview whereby an interviewee, a 29-year-old Chinese worker from Sichuan (South-West China) working at the Shell CSPC site recounted his actual experience of a fatigue-related accident as follows:

> I was working on the weekend night shift. At about 3.00 a.m., I felt drowsy and physically 'drained' as I was working on a double shift. I took a short cut (failure by individual worker to follow safety procedure) due to time pressure during the commissioning of gas-in and gas-out. I also took off my gas mask (failure to use PPE) because it was cumbersome. Besides, my supervisor didn't mind it. At the same time, my mind drifted to my family back in my hometown and how I missed them (distracted by other concerns and emotional distress). I do not know why (judgement impairment) I turned on the safety valve of the gas tank even though there was a safety signage, which indicated 'DO NOT TOUCH'. Furthermore, my supervisor did not warn me that methane gas could catch fire easily (inadequate communication between supervisor and worker and lack of safety knowledge of hazard presents). Immediately, methane gas (unsafe work condition) escaped and my workplace caught fire, followed by an explosion. Luckily, I escaped!

The qualitative finding as exemplified in the interview transcript validated studies by Dawson and Reid (1997) that a fatigued worker can have performance impairment equivalent to a blood alcohol concentration (BAC) of 0.10% given more than 20 hours of sustained wakefulness. This probably explains why the interviewee had unconsciously '… turned on the safety valve …'. The human error has set up a chain of events leading to explosion at the workplace. The illustration further corroborates studies by Folkard and Tucker (2003) and Nachreiner (2000) that a fatigued night shift worker's level of sobriety is constantly fluctuating, and sustaining alertness is difficult. This also probably explains how easily he could be easily distracted by other concerns. Indeed, the distraction theory of Hinze (1996) and the 'constraints-response' theory of Suraji *et al.* (2001) have indicated that distraction '… my mind drifted …' and emotional distress (dismal factor) '… I missed them …' can cause responses that create inappropriate actions (proximal factors) '… I took off … gas mask …,' thus leading to accidents. Furthermore, physical fatigue, mental state and time pressure could be the reason why workers '… took a short cut …'. Interestingly, in the first study 59% of all the stakeholders unanimously ranked failure of individual workers to follow safety procedures as the second most critical risk perceived to cause accidents. While the chi-squared test showed no significant difference among the views of the three stakeholders for this risk (p = 0.977), there was significant difference in the other two risk items: inadequate communication between supervisors and workers (ranked ninth) (p = 0.007*) and workers' failure to use PPE (ranked eighth) (p = 0.006*) (Table 2).

The former finding validated the interviewee's statement '… my supervisor did not warn me …' and is consistent with a study by Tam and Fung (1998) that safety supervisors have minimal communication with

Table 2 Comparison of the top 10 rankings among three groups of stakeholders

		Endorsement by respondents							
		Workers		Supervisors		Managers			
Rank	Respondent who said 'yes' to top 10 risk items	Rank	Yes (%)	Rank	Yes (%)	Rank	Yes (%)	χ^2	p-value^
1	Fatigue	1**	189 (79)	1**	22 (71)	1**	15 (79)	0.979	0.613
2	Failure of individual workers to follow safety procedures	2**	144 (59)	2.5**	21 (60)	3**	12 (57)	0.046	0.977
3	Lack of safety knowledge of hazards present	4.5	124 (50)	4	19 (56)	5	11 (52)	0.372	0.83
4	Improper use of equipment	3**	126 (51)	7	16 (47)	6	10 (48)	0.282	0.869
5	Fire or explosion	6.5	121 (48)	2.5**	21 (60)	7	9 (45)	1.827	0.401
6	Defective equipment	8.5	114 (46)	5	18 (51)	2**	12 (60)	1.762	0.414
7	Inadequate work place layout	4.5	119 (50)	9	17 (46)	8	5 (23)	5.858	0.053
8	Failure to use PPE	6.5	119 (48)	10	10 (29)	9	4 (19)	10.14	0.006*
9	Inadequate supervisor–worker communication	8.5	114 (46)	6	18 (47)	10	2 (10)	9.881	0.007*
10	Emotional disturbances	10	102 (42)	7	16 (47)	4	11 (55)	1.481	0.477

Notes: ** Top three ranked risk items. * Significance at the 0.05 level (one-tailed) $\chi 2$ refers to chi-squared test.

^If p-value is < 0.05, it implies that the views of the three stakeholders diverged for that particular risk. If p-value is > 0.05, it implies that the views of the three stakeholders converged for that particular risk.

their workers and make little effort to reinforce safe behaviour among them. This further corroborates the finding by Haslam *et al.* (2005) that sometimes supervisors are complicit in safety failures as exemplified in the transcript '… my supervisor … didn't mind'. The risk of accident is further compounded by the interviewee's ignorance that methane gas is highly inflammable. Indeed, this lack of safety knowledge of hazards present was ranked as the third most critical risk in the first study.

Hence, the tenor of the argument, based on the data mining analysis which is augmented by the first study and triangulated by the qualitative finding is that fatigue played a central role in mediating accidents among the Chinese workers by triggering or 'lifting' a confluence of associated risk items (antecedents).

Fatigue and accident mitigation

A previous study by Bültmann *et al.* (2002) has indicated that fatigue is a multi-dimensional phenomenon encompassing physical, mental, emotional and other behavioural aspects. However, the empirical evidence in the study has demonstrated that fatigue is a far more complex phenomenon. In order to provide further insights into the complex relationship between fatigue and a synergetic bundling of mediating variables, a diagram based on Association Rule 4 (Figure 3) was constructed. The objective was to demonstrate the inter-relationship of fatigue with three antecedents and their inter-correlation with five exogenous risks (defective equipment, improper use of equipment, improper use of tools, failure to use PPE, improper use of PPE).

In identifying and quantifying the strength of the interaction of each identified risk item and its relationship with fatigue, the association rule has provided new knowledge and important theoretical insights into accident mitigation. For instance, although the three antecedents are associated with fatigue and inter-correlated with five exogenous risks (defective equipment, improper use of equipment, improper use of tools, failure to use PPE and improper use of PPE), the strongest link is between distracted by other concerns and failure of individual workers to follow safety procedures (r_s = 0.152**). However, distraction by other concerns is also highly correlated with five other exogenous risk items. This implies that an increase in distraction is associated with an increase in the five other risks since the correlations are positive.

This newfound knowledge provides an alternative solution to accident mitigation. That is, identifying the strategic risk items that have direct impact (strongest link) on the reduction of fatigue is significantly and strategically more important, rather than trying to control *all* the risk items that are correlated with the antecedents. This argument redefines the existing knowledge that all risk must be controlled or mitigated in order to avert any impending accident. On the other hand, controlling individual antecedents in isolation (e.g. training workers to follow safety procedures without reducing their emotional overload or improving communication between supervisor and workers) will also not alleviate fatigue, as these antecedents are synergistically related to each other and correlated with other exogenous risks. Therefore, reducing the workers' emotional overload[11] and

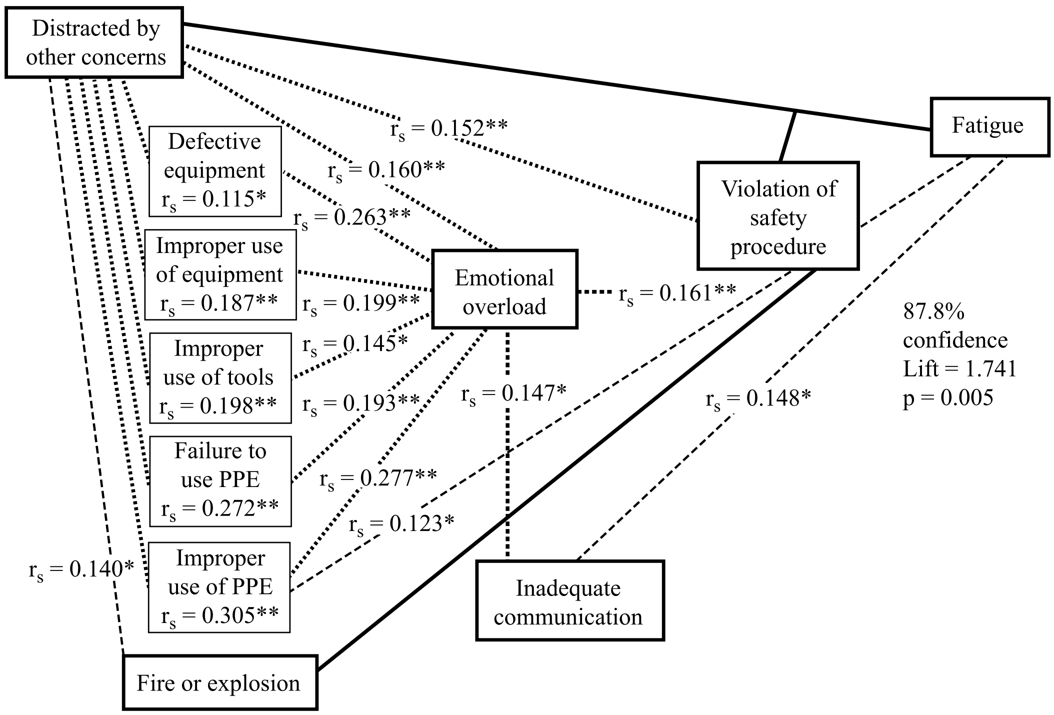

Figure 3 Association Rule 4: Fatigue in association with distracted by other concerns, fire or explosion and failure of individual workers to follow safety procedures
Notes: Violation of safety procedure refers to failure of individual workers to follow safety procedure. *significance at the 0.05 level (2-tailed), **significance at the 0.01 level (2-tailed). r_s refers to Spearman's rank correlation coefficient.

improving communication between supervisor and workers[12] would have a greater influence on reducing fatigue.[13] These two correlations are not only significant but also belong to the systematic cause of accidents and hence provide the strongest link to reducing fatigue as compared to eliminating the three antecedents which are symptoms of the immediate cause of accidents (Figure 1). However, the best strategy is to reduce the fatigue level of the workers (e.g. by giving them time to recuperate) since this would reduce the impact of the three antecedents and the exogenous risks respectively. Therefore, it can be argued that fatigue is not only a trigger risk factor but also the lynchpin in the quest to reduce accidents. The significant insight gained from understanding the complex synergetic bundling of mediating variables (antecedents and their inter-correlated risks) and their relationship with fatigue is central to risk management and its impact significance on accident mitigation.

Conclusions

The purpose was to identity the new and emergent risk items (from the top 10 ranked items) and to investigate their roles in mediating and mitigating site accidents among workers.

The discoveries of fatigue and emotional disturbance (mental state) are both unique and their relevance highly significant. Both risks have hitherto been under-researched in the construction industry and their contribution to accident perhaps underestimated. The finding of fatigue and its complex relationship with a synergetic bundle of associated risks in influencing the occurrence of accidents has encapsulated the latest development in the understanding of construction risk management. The new discovery confirms the need to consider fatigue as a complex multidimensional phenomenon. It further provides a plausible explanation as to the likelihood or probability of *how* and *why* accidents might occur with fatigue as the trigger risk item and a lynchpin to accident mitigation. With the increase in the global construction of oil and gas and LNG projects (Jensen, 2004), the findings are both timely and the research well justified.

The theoretical implications of the study are that it integrates, validates and expands on the multiple causation theory of accidents to provide new perspectives on accident mitigation gained from the oil and gas sector of the construction industry. In the realm of professional practice, management and HS practitioners would be wise to undertake a review of their existing HS policies and incorporate fatigue and mental stress into their safety audit. Workers at risk could be screened for fatigue at regular intervals. Furthermore, various health and safety strategies would be required to mitigate accidents since fatigue is associated with a synergetic bundle of risks.

While the relationship between fatigue and accidents has been well researched, albeit perhaps not in the construction industry, the research has resonance well beyond the four case studies in mainland China. It provides a point of departure for new trajectories in advanced economies where safety research is more established (e.g. North American and European countries). Although the study also lends support for the concern related to working extended hours, which characterize the many forms of employment in this industry, the conclusion drawn in the study cannot be generalized to all construction activities. Sample biasness may sometimes influence the selection of fatigue and this may alter the conclusions. For instance, Houston and Allt (1997) maintained that sometimes respondents might be motivated to report health and safety issues (e.g. fatigue) in order to increase attention and awareness of working extended hours to the management. Furthermore, the study is based on self-reported measures, and according to Ono *et al.* (1991) and Daniels and Guppy (1995) this method introduces the issue of subjectivity (e.g. the feeling of 'fatigue' and 'mental state/stress').

Furthermore, the 'true' definition of the two variables may be lost in translation from English to Mandarin, due to conceptual ambiguity. Hence, the author cannot be sure that the interpretation of the variables is the same among the individual respondents within the study or across the different study sites. Therefore, generalizing the findings within the study and with other studies in the West can be problematic. For example, working 'long hours' may be considered to result in fatigue, but what constitutes 'long hours' in the West may be considered 'short hours' in mainland China as Chinese society may perceive working 'long hours' as an industry norm. The Chinese labour law and regulations on working extended hours, and the absence of unions, could compound the problem further.

Despite these study limitations, the research has nevertheless created a new response to the problem of accident causation and an alternative view to accident mitigation. It has also opened new opportunities for academic inquiry, setting new agendas for future research directions as a 'spin off' from the study (e.g. fatigue risk management in construction).

Acknowledgements

The author would like to thank academics from the University of Sydney: Emeritus Professor John Small, Emeritus Professor John Robinson, Dr Nigel Balaam and the University of Hong Kong: Professor Steve Rowlinson and the reviewers for their constructive comments. Special thanks also to the following key personnel for their support in the research: Jack Brinly, Zhang Zhiliang, Rick Spivey and Aidan Hayes from BP SECCO, Paul Milican from BP LPG, Paul Lo and Greg Willms from Shell Nanhai, Exxon Mobil Fujian, David Marshall, Paul Keeler, Ian Ross, Thomas King and Marty Whether from Guangdong LNG, Ross Gibson and Gerry Baker from Amec Engineering and Consulting (Shanghai) Co. Ltd, Steve Katzman from Betchel China Inc., Jim Gibson from Foster Wheeler International E and C (Shanghai) Co., James Russo from ABB Lummus Global, David Knights from Saipem (Beijing) Technical Services Co. Ltd, Brian Gillon, Ray Brewster and Jon Kitching from Leighton Contractors (Asia) Ltd, Allan Paton, Tim Hallworth, and Jesse Hau from Gammon Construction (China) Ltd.

Notes

1. The accident not only wreaked havoc on the environment, but also caused extensive damage to the reputation and economic loss to the company. In September 2010, BP announced an expected payout of US$20 billion in compensation to businesses (fishermen, hoteliers and retailers) affected by the oil spill (International Business Times News Online, 2010).
2. Managers refer to expatriate and Chinese safety, construction, and project managers.
3. US$2.8 billion project.
4. US$4.2 billion project.
5. US$3.7 billion project.
6. Two hundred and twenty-six (78%) respondents said 'yes' to fatigue while 64 (22%) said 'no' to fatigue. Two hundred and ninety valid responses were recorded for this risk item, fatigue, with 30 missing values.
7. If lift <1, then the occurrence of *A (fatigue)* is *negatively correlated* with the occurrence of *B (antecedents)*. This means that the occurrence of fatigue *does not* imply the occurrence of the antecedents and vice versa. On the other hand, if lift >1 then *A* and *B* are *positively correlated*. This means that the occurrence of fatigue is associated with the occurrence of the antecedents and vice versa.
8. Fatigue is one of the 11 risk items under physical capability in Section III Q2 of Figure 1.
9. Emotional disturbance is one of the eight risk items under mental state in Section III Q4 of Figure 1.
10. Extended hours included overtime, shiftwork and compressed weekends.
11. Emotional overload is one of the eight risk items under mental stress in Section III Q5 of Figure 1.
12. Correlation of emotional overload and inadequate supervisor-worker communication, $r_s = 0.147$*.
13. Correlation between inadequate supervisor–worker communication and fatigue, $r_s = 0.148$*.

References

Agrawal, R. and Srikant, R. (1994) Fast algorithms for mining association rules, in *Proceedings of the 20th International Conference on Very Large Data-bases (VLDB-94),* Santiago de Chile, Chile, 12–15 September, pp. 487–99.

Aksorn, T. and Hadikusumo, B.H.W. (2008) Critical success factors influencing safety programme performance in Thai construction projects. *Safety Science,* **46**, 709–27.

Anderson, R. and Lagerlof, E. (1983) Accident data in the New Swedish information system on occupational injuries. *Ergonomics,* **2**(1), 33–42.

Barofsky, I. and Legro, M. (1991) Definition and measurement of fatigue. *Reviews of Infectious Diseases,* **13**, 94–7.

Bültmann, U., Kant, I.J., Schröer, C. and Kasl, S. (2002) The relationship between psychosocial work characteristics and fatigue and psychological distress. *International Archives of Occupational and Environmental Health,* **75**(4), 259–66.

Cheng, E.W.L., Li, H., Fang, D.P. and Xie, F. (2004) Construction safety management: an exploratory study from China. *Construction Innovation,* **4**(4), 229–41.

Cox, S. and Tait, R. (1998) *Safety, Reliability and Risk Management: An Integrated Approach,* Butterworth-Heinemann, Oxford.

Daniels, K. and Guppy, A. (1995) Stress, social support and psychological well-being in British accountants. *Work and Stress,* **9**, 432–47.

Dawson, D. and Reid, K. (1997) Fatigue, alcohol and performance impairment. *Nature,* **388**(6639), 235.

Delmater, R. and Hancock, M. (2001) *Data Mining Explained: A Manager's Guide to Customer-Centric Business Intelligence,* Digital Press, Boston.

DiMattia, D.G., Khan, F.I. and Amyotte, P.R. (2005) Determination of human error probabilities for offshore platform musters. *Journal of Loss Prevention in the Process Industries,* **18**(4–6), 488–501.

Donaghy, R. (2009) *One Death Is Too Many: Inquiry into the Underlying Causes of Construction Fatal Accidents,* Report to the Secretary of State for Work and Pension, TSO, London.

Folkard, S. and Tucker, P. (2003) Shiftwork, safety and productivity. *Occupational Medicine,* **53**, 95–101.

Gander, P.H., Merry, A., Millar, M.M. and Weller, J. (2000) Hours of work and fatigue related error: a survey of New Zealand anaesthetists. *Anaesthesia and Intensive Care,* **28**(2), 178–83.

Gyi, D.E., Haslam, R.A. and Gibb, A.G.F. (1998) Case studies of occupational health management in the engineering construction industry. *Occupational Medicine,* **48**(4), 263–71.

Gyi, D.E., Gibb, A.G.F. and Haslam, R.A. (1999) The quality of accident and health data in the construction industry: interviews with senior managers. *Construction Management and Economics,* **17**(2), 197–204.

Hamid, A.R.A., Majid, M.Z.A. and Singh, B. (2008) Causes of accidents at construction sites. *Malaysian Journal of Civil Engineering,* **20**(2), 242–59.

Haslam, R.A., Hide, S.A., Gibb, A.G.F., Gyi, D.E., Pavitt, T., Atkinson, S. and Duff, A.R. (2005) Contributing factors in construction accidents. *Applied Ergonomics,* **36**(4), 401–15.

Hinze, J. (1996) The distraction theory of accident causation, in *Proceedings of the 1st International Conference on Implementation of Safety Health on Construction Sites,* The Netherlands, 16 September, pp. 357–84.

Houston, D. and Allt, S. (1997) Psychological distress and error making among junior house officers. *British Journal of Health Psychology,* **2**, 141–51.

Hsu, S.H., Lee, C.C., Wu, M.C. and Takano, K. (2008) A cross-cultural study of organizational factors on safety: Japanese vs. Taiwanese oil refinery plants. *Accident Analysis and Prevention,* **40**(1), 24–34.

International Business Times News Online (2010) BP says oil spill compensation payout rate soars, available at http://uk.ibtimes.com/articles/63899/20100920/bp-says-oil-spill-compensation-payout-rate-soars.htm (accessed 20 September 2010).

Jackson, S.A. and Loomis, D. (2002) Fatal occupational injuries in the North Carolina construction industry, 1978–1994. *Applied Occupational and Environmental Hygiene,* **17**(1), 27–33.

Jensen, J.T. (2004) *The Development of a Global LNG Market: Is it Likely? If so When?,* Oxford Institute for Energy Studies, Alden Press, Oxford.

Khan, F.I. and Abbasi, S.A. (1998) Techniques and methodologies for risk analysis in chemical process industries. *Journal of Loss Prevention in the Process Industries,* **11**, 261–77.

Kheni, N., Andy, D. and Gibb, A. (2008) Health and safety management in developing countries: a study of construction SMEs in Ghana. *Construction Management and Economics,* **26**(11), 1159–69.

Koehn, E. and Reddy, S. (1999) Safety and construction in India, in Singh, A., Hinze, J. and Coble, R.J. (eds) *Proceedings of the 2nd International Conference of CIB Working Commission W99, Implementation of Safety and Health on Construction Sites,* Honolulu, Hawaii, Taylor & Francis, Lisbon, Portugal, pp. 39–44.

Lamond, N. and Dawson, E. (1999) Quantifying the performance impairment associated with fatigue. *Journal of Sleep Research,* **8**(4), 255–62.

Liska, R.W., Goodloe, D.W. and Sen, R. (1993) *Zero Accident Techniques,* Report for the Construction Industry Institute, University of Texas, Austin.

McLain, D.L. and Jarrell, K.A. (2007) The perceived compatibility of safety and production expectations in hazardous occupations. *Journal of Safety Research,* **38**(3), 299–309.

Nachreiner, F. (2000) Extended work hours and accident risk, in Marek, T., Oginska, H., Pokorski, J., Costa, G. and Folkard, S. (eds) *Shiftwork 2000—Implications for Science, Practice and Business,* Institute of Management, Jagiellonian University, Krakow, pp. 29–44.

Ono, Y., Watanabe, S., Kaneko, S., Matsumoto, K. and Miyako, M. (1991) Working hours and fatigue of Japanese flight attendants. *Journal of Human Ergology,* **20**, 155–64.

Parkhe, A. (1993) 'Messy' research, methodological predispositions, and theory development in international joint ventures. *Academy of Management Review,* **18**(2), 227–68.

Pate-Cornell, M.E. and Murphy, D.M. (1996) Human and management factors in probabilistic risk analysis: the SAM approach and observations from recent applications. *Reliability Engineering and System Safety,* **53**(2), 115–26.

Petersen, D. (1975) *Safety Management: A Human Approach,* Aloray, Englewood, NJ.

Reason, J.T. (1990) *Human Error,* Cambridge University Press, New York.

Rowlinson, S.M. (1997) *Hong Kong construction – site safety management,* Sweet and Maxwell Asia, Hong Kong.

Sui, O.L. (2001) A study on safety climate, work stress, and safety performance among construction workers in Hong Kong: a facet approach, in Elizur, D. (ed.) *Facet Theory: Integrating Theory Construction with Data Analysis,* Matfyz, Prague, Czech Republic, pp. 311–22.

Suraji, A., Duff, A.R. and Peckitt, S.J. (2001) Development of causal model of construction accident causation. *Journal of Construction Engineering Management,* **127**(4), 337–44.

Tam, C.M. and Fung, I.W.H. (1998) Effectiveness of safety management in Hong Kong. *Construction Management and Economics,* **16**, 49–55.

Tam, C.M., Zeng, S.X. and Deng, Z.M. (2004) Identifying elements of poor construction safety management in China. *Safety Science,* **42**(7), 569–86.

Tweeddale, M. (2003) *Managing Risk and Reliability of Process Plants,* Gulf Professional Publishing, Oxford.

Zeng, S.X., Tam, V.W.Y. and Tam, C.M. (2008) Towards occupational health and safety systems in the construction industry of China. *Safety Science,* **46**(8), 1155–68.

Zhou, Q., Fang, D. and Wang, X. (2007) A method to identify strategies for the improvement of human safety behaviour by considering safety climate and personal experience. *Safety Science,* **46**(10), 1406–19.