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Published in

Safety Science

Volume 105, June 2018, Pages 158-166

https://doi.org/10.1016/j.ssci.2018.02.006

Accident types and barrier failures in the construction industry

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Abstract

The paper identifies frequent accident types in the construction industry, characterises the accident sequence, and identifies barrier failures for the most frequent accident types. 176 accidents in the Norwegian construction industry investigated by the Norwegian Labour Inspection Authority in 2015 are analysed. The most frequent accident types include: fall from roof, floor or platform; contact with falling objects; fall from scaffold; and contact with moving parts of a machine. A comparison of the study sample to other injury samples, showed that the distribution of accident types varied regarding severity and different construction types. This can be explained by differences in work type, hazard, and energy type and energy amount. An analysis of barrier failures showed that many accidents are explained by the lack of physical barrier elements. The results indicate that there is significant potential for accident prevention in the construction industry by systematic barrier management.

Keywords:

Construction industry

Barrier failures

Accident types

1 Introduction

The construction industry in Norway has one of the highest numbers of fatal injuries and incident rates compared with other industries. The average incidence rate for fatalities during 2012-2016 was 4.1 per 100,000 employees (Labour Inspection Authority, 2017). An increase in the annual number of fatalities, and some major, dramatic accidents, led to an initiative from stakeholders in the Norwegian construction industry to establish a tripartite cooperation with a vision-zero-approach. The cooperation expressed a need for further knowledge on frequent accident types and their causal factors. Clients and contractors produce injury statistics for their projects and hence have an overview of the less severe injuries. However, they rarely experience severe accidents themselves. As a result, none of the actors in the industry have a significant number of cases of severe accident types and their barrier failures.

The purpose of this study is 1) to identify frequent accident types and 2) to analyse barrier failures to establish a knowledge base for prioritising and developing preventive measures in the construction industry. Producing relevant knowledge about accidents is problematic as the national data on accidents and injuries (like other countries), does not '… generally permit detailed analysis of causes beyond the identification of the mechanism and agency of injury' (Cooke and Lingard, 2011, p. 279). The main study sample in this research consists of 176 severe construction accidents investigated by the Norwegian Labour Inspection Authority (LIA) in 2015. This paper is limited to studying mainly proximate causes and incident types. Contributing factors in the organisation are not addressed.

There exist some statistics and studies showing distribution of incident types. However, it is problematic to compare the different studies and statistics since there are different categories used for describing accidents, e.g. 'deviations', 'cause', 'accident/injury types' and 'central events'. However, 'fall from height' dominates in most studies and statistics. Other frequent 'accident types' are falling/collapsing objects, moving vehicles, moving machine parts, and electricity. In Europe (EU28), 782 fatal construction accidents were registered in 2014 (Eurostat, 2017). The most frequent 'deviations' were: fall of persons (26%); breakage/fall/collapse etc. of material agent (20%); and loss of control of machines, equipment, tools etc. (19%) (Eurostat, 2017). The distribution of 'deviations' for non-fatal accidents was somewhat different. In a study of deaths from injuries among construction workers in North Carolina 1988-1994, Lipscomb et al. (2000) found that work related deaths were most often 'caused by' motor vehicles (21%), falls (mostly roofs and scaffolds) (20%), machinery (15%), electrocutions (14%), and falling objects (10%). In a Dutch study of 'accident types' in the construction industry, Ale et al. (2008) found that the most frequent 'accident types' were fall from height (roof, floor, platform), contact with falling/collapsing objects, fall from ladder, fall from scaffold, and contact with moving parts of a fixed machine. Both the statistics from Eurostat (2017) and Ale et al. (2008) show differences in the distributions of fatal vs. non-fatal accidents. Based on a review of construction safety literature using mortality data, Swuste et al. (2012) concluded that the most frequent 'central events' were: falling from height; contact with falling or collapsing objects; contact with electricity; contact with moving machinery parts; falling from a moving platform; contact with hoisted, hanging, swinging objects; hit by vehicle; squeezed between or against something; and contact with objects thrown from machine.

The construction industry is not homogenous, which also implies that incident types and barrier failures can vary regarding the type of project (e.g. building, infrastructure, refurbishment), project phase and project size and complexity. Research has demonstrated that causal factors differ in different settings, for instance between countries (Cameron et al., 2008; Spangenberg et al., 2003), and construction project features (Manu et al., 2010).

The framework used in this analysis is based on three elements that are basic in many accident causation models, namely hazards, barriers/defences and loss (e.g. Haddon, 1980; Reason et al., 2006). The analysis focuses on proximate factors in the accident sequence. Distal, organisational factors are not covered in this paper.

2 Study samples

The main study sample consists of 176 construction accidents investigated by the Norwegian LIA in 2015. This sample gives sufficient descriptions of the accident sequence as well as a sufficient number of recent accidents. The study sample is limited to accidents investigated by the LIA for one year. In 2015, LIA carried out investigations of 189 construction accidents, involving 210 companies. Seven of the 189 accidents were excluded from the sample since they did not take place during construction work or at constructions sites, and six accidents were excluded due to lack of sufficient information about the accident. Hence, the main study sample is 176 accidents involving 184 injured persons, of which 4 were fatalities.

According to the Norwegian Work Environment Act, occupational accidents that have led to fatal- or severe injuries must be notified to the police and the LIA. Severe injury here means any harm, (physical or mental), that results in permanent or prolonged incapacitation. There is guidance on LIA's website describing nine characteristics that indicate severe injury, e.g. injuries to head, skeleton, internal organs, loss of body part, poisoning, unconsciousness, metabolism/frost injury, hypothermia, and injuries that lead to hospitalisation (Labour Inspection Authority, 2017). When the LIA is notified of an accident, the LIA decide whether to complete an investigation based on assessments of potential severity and available inspectors. These are the criteria for selecting accidents for the main study sample:

1. At least one construction company involved
2. Happened during construction work
3. Inspected by the LIA in 2015

Most construction accident statistics do not include workers employed by non-construction companies that are injured in construction accidents, e.g. temporary employment agencies. Criteria 1 and 2 ensure that these workers are included.

One investigated accident can contain many documents and normally consists of the notification of the accident, accident reports from the LIA and the company, and other letters between the LIA and companies. When an accident is reported by mail or phone to the LIA, a checklist is used to collect information about the accident to decide whether an investigation is going to be carried out. During the investigation, the inspectors use another checklist to investigate if there have been any violations of the law and to collect information about the course of events. After the investigation, the inspectors produce an investigation report that in most cases includes a description of the accident sequence, causal factors, and violations of the law when identified. In most cases, the investigated company is decreed to produce an accident investigation report and a plan including measures to prevent similar accidents.

The amount of information on the accidents varies significantly. Some cases have only one document while others have 50. Some cases are sparsely described and six accidents were excluded due to lack of sufficient information. Other accidents have rich descriptions and are investigated by professional accident investigators.

This research includes all data collected from the reporting of the accident and the whole process related to the investigation. Four analysts were engaged in finding relevant documents and extracting relevant qualitative information from the accidents into a word document consisting of 84,000 words. Central issues were assessed and organised in variables in an Excel document.

2.1 Samples compared to the main study sample

The main study sample is compared to four other samples of construction injuries representing different degrees of severity (Table 1). The aim of the comparison is to assess representativeness of the study sample and relations between accident severity and distribution of accident types.

The official number of employees in the Norwegian construction industry in 2015 was 206,000 and the average number of fatalities per 100,000 employees in the 2012-2016 period was 4.1 fatalities. It is likely, however, that the level of injuries in construction is underestimated since staffing agencies or subcontractors that are not construction companies employ many of the injured workers.

Table 1. Overview of samples of injuries in the Norwegian construction industry

Sample name	Description	Data period	Injuries in the sample	Number injuries per year	Estimated average severity (order)
'Main study sample'	Accidents investigated by the LIA in 2015	2015	184 (176 accidents)	-	Medium/high (2)
'Fatal'	Fatal injuries	2000-2014	131	10 (average 2012-2016)	High (1)
'Inspection'	Injuries reported to the LIA	2011-2016	1758	293 (average 2011-2016)	Medium (3)
'Insurance'	Injuries (insurance claims) reported to the Labour and Welfare Administration (LWA)	2015	1783	1 783	Medium (4)
'Survey'	Labour force survey (LFS) 2013	2013	41	9 000 - 10 000	Low (5)

The main study sample is described above. The ‘fatal’ sample is fatal injuries reported to the LIA by the employer, police or health services (Table 1). Sometimes the LIA captures fatalities via media or other sources. It is estimated that the fatal injuries represent nearly 100 % of the fatal construction injuries. The ‘inspection’ sample is injuries reported to the LIA and is similar to the main study sample. One difference is that the ‘inspection’ sample includes *all injuries reported to the LIA* 2011-2016, while the study sample only includes reported injuries that were investigated in 2015. Another difference is that the ‘inspection’ sample includes only employees in construction companies, while the main study sample also includes employees in non-construction companies (e.g. hired workers) injured during construction work. The level of underreporting is unknown. The ‘insurance’ sample is occupational injuries that lead to medical treatment or lead to work disability reportable to the Labour and Welfare Administration (LWA). These are the public injury statistics in Norway. The injury notification forms, including accident type, must be filled in by the employer, but are sometimes filled in by the injured worker. The level of underreporting is unknown (Statistics Norway, 2016).

The ‘survey’ sample is based on telephone interviews of a representative sample of workers. One question asked if the interviewees had been injured in a work accident the last 12 months. 915 of these workers were construction workers of which 41 were injured. The same accident type variable was used as in the other samples, but the sample lacks some categories. About 50 % of these injuries did not lead to sick leave, so the average severity is low.

3 Methods

Descriptive epidemiology is an often-used method in investigation of construction accidents on a national, regional, or company level (Swuste et al., 2012). Descriptive epidemiology seeks to summarise conditions based on person, place, and time by analysing the pattern of health outcomes (e.g. accidents) (Aschengrau and Seage, 2007). This research uses a similar approach to that used in industrial settings, so-called ‘incident concentration-analysis’ (Kjellén and Albrechtsen, 2017). The purpose of incident concentration analysis is to identify clusters of incidents with common characteristics. The concentrations indicate where to prioritise safety measures and types of measures to prioritise. Incident-concentration analysis in industrial settings is carried out in several ‘dimensions’. The basic assumption is that each industrial system has its own clusters of accidents, mainly decided by the types of energies involved in the production. The steps in the incident concentration analysis used in this research are to:

1. Establish uni- and bi-variate distributions for different dimensions
2. Select concentrations making up a significant portion of the total number of records (e.g. 5-10 out of 50 records) with similar characteristics

3. Analyse these concentrations in more detail
4. Look for similarities in activities, sequence of events and energy involved.

3.1 Framework for analysis of the accident sequence

The framework used in this analysis is based on three elements that are basic in many accident causation models – namely hazards, barriers/defences, and loss (e.g. Haddon, 1980; Reason et al., 2006). An accident involves hazards coming into contact with objects (e.g. workers) as the result of failures in one or more barriers (Haddon, 1973).

The cases in this analysis are construction workers injured in accidents, which represent the 'loss'. A clarification and operationalisation of the terms 'hazards' and 'barriers' is necessary.

3.1.1 Energy, hazards, and accident types

The first step in this analysis is to identify hazards that are frequently involved in accidents and how they affect workers. Haddon (1973) addressed the notion that injury occurs through the transfer of energy (kinetic, thermal, chemical, electrical, and ionising radiation). An injury occurs when '… energy is transferred in such ways and amounts, and at such rates, that inanimate or animate structures are damaged' (Haddon, 1973, p. 41). A hazard is a '... potential source of injury or damage to health of people, or damage to the environment or material assets' (Kjellén and Albrechtsen, 2017, p. 476). There are several variables for categorising 'accident types' (e.g. Eurostat and ILO), and each 'accident type' is linked to a specific hazard which is a source of energy. An accident type variable helps to identify how a hazard affects a worker. In Norway, the same accident type variable is used in the samples described above which makes it possible to compare the distributions of accident types across the samples. To identify more detailed accident types, a variable developed for occupational accidents by the WORM project (Workgroup Occupational Risk Model) in the Netherlands (Hale et al., 2007) is utilised. This variable is based on the bowtie and the aim behind the variable is to '… describe all types of occupational accidents in a set of generic descriptions, or scenarios, linking the development of each type of accident to the possible barriers …' (ibid. p. 1701). The object behind the development of the variable was to support companies in their risk analysis and prioritisation of prevention. The variable has 36 different 'scenarios' and is also used in the 'Storybuilder' tool (Bellamy et al., 2007) and in a study of construction accidents in the Netherlands (Ale et al., 2008).

3.1.2 Barrier failures

The second step in this analysis is to identify failed barriers and discuss preventive measures. There is no generally accepted definition of barriers (Sklet, 2006). In this paper, we apply Kjellén and Albrechtsen's (2017, p. 130) definition of a barrier as '… a set of system elements (human, technical, organisational) that as a whole provide a barrier function with the ability to intervene into the energy flow to change the intensity or direction of it'. A *barrier function* is 'the ability of a barrier to intervene into an accident sequence to eliminate or reduce loss', and the *barrier system* is '… a set of interacting, human, technical and organisational elements that make up the barrier function'. Some barriers are specifically made for safety, for example, guardrails and hard hats; others are part of a production system or structure, for instance building materials and scaffold floor. Some barriers are a mix of these functions. The categories of barrier element failures in this research are developed inductively based on the qualitative descriptions of the accident sequence in the material.

Haddon (1980, p. 8) identified '... generic strategies that encompass all of the tactics that may be used to reduce damage'. These strategies are also called 'energy barriers' (Trost and Nertney, 1995). The first strategy helps us consider measures that can eliminate basic hazards, while the other nine help us consider measures that can interrupt the injury process at different stages. Haddon's strategies encourage a fundamental way of thinking about the processes by which injuries occur and the ways in which they can be prevented (Runyan and Baker, 2009). The strategies focus mainly on passive measures that will have a more universal and lasting impact than behavioural strategies. These strategies are not mutually exclusive and combinations of measures are often recommended.

Kjellén and Albrechtsen (2017) order Haddon's strategies (1980) so that the primary strategies are related to the hazard (energy source) (strategy 1-5), separation of the hazard and object (strategy 6, 7), and the vulnerable object (strategy 8-10) (Table 2). Strategies 9 and 10 are beyond the scope of this analysis.

Table 2. Haddon's 10 countermeasure strategies for reducing loss. Based on Haddon (1980) and Kjellén and Albrechtsen (2017).

Related to the hazard (energy source)	Related to the separation of the hazard from the object (worker)	Related to the vulnerable object (worker)
1.Prevent the creation of the hazard	6.Separate, in time or space, the hazard and the vulnerable target	8.Make the object more resistant
2.Modify relevant basic qualities of the hazard	7.Separate the hazard and object by physical barriers	9.Limit the development of loss
3.Reduce the amount of the hazard 4.Prevent the release of the hazard 5.Modify the rate or spatial distribution of release of the hazard from its source		10. Stabilise, repair and rehabilitate

Trost and Nertney (1995) describe three types of limitations in barriers. One limitation is that *barriers are not practical* (NP) due to the energy source, cost of the barrier etc. Another limitation is that *barriers fail* (BF), for instance that physical barriers erode and procedural barriers deteriorate through weak change control. A third limitation is when *barriers are not used* (NU). Most of the accidents in this material do not have details to assess deficiencies in the total barrier systems. The aim is to identify main failures in *physical barrier elements* that contributed to the accidents.

4 Results

Table 3 shows background data for injured persons and the accidents in the main study sample.

Table 3. Background data for the 176 accidents/184 injuries in the main study sample in percentages

Sex of involved workers (%)		Age of involved workers (%)		Nationality of involved workers (%)		Potential fatality of accident (%)	
Male	98.3	15-19	8.4	Norway	62.0	Fatality	2.4
Female	1.7	20-24	13.8	Other Nordic countries	5.6	Likely	46.5
Tot.	100.0	25-39	29.9	Eastern Eur.	25.8	Possible	25.9
		40-54	34.1	Other Eur. countries	6.1	Not possible	25.3
		55-67	12.6	Non-Eur.	0.6	Tot.	100.0
		67<	1.2	Tot.	100.0		
		Tot.	100.0				

Only 3 of the injured workers were women. The average age was 38 years, 64% of the injured were between 25 and 55 years, and 22 % were younger than 25. The material does not always give information about the conditions of employment, but at least 18 % were hired workers and 9 % apprentices or hired for a summer job. 38 % of the injured persons had foreign citizenship, 26 % were from Eastern Europe, with the majority from Poland.

A method used by Haslam et al. (2003) was also used in this research to indicate potential fatality. Information from the accidents was used to evaluate alternative outcomes and to assess the outcome if the injured person had been in a slightly different location or if a different part of the body had been involved. *Likely fatality* required only a minor change in circumstances and *possible fatality* required a number of circumstances to change. 47% were assessed to be *likely* fatalities, 26% *possible* fatal accidents, and 25% were *not possible* fatalities. Most of the accidents assessed not to be likely or possible fatalities, were accidents using a saw.

4.1 Accident types and severity

The accident types in the main study sample are compared to four other samples of injury data representing four different degrees of severity (Table 1 and Table 4). The purpose of the comparison is to assess the representativeness of the study sample and relations between severity and accident types.

Table 4. Accident types (%) for injured persons in the construction industry for different samples. The order of the top five accident types in parenthesis.

	'Study sample'	'Fatal'	'Inspection'	'Insurance'	'Survey'

Fall	48 (1)	33 (1)	42 (1)	29 (1)	19 (3)
Hit by object	24 (2)	22 (2)	16 (3)	27 (2)	27 (2)
Cut by sharp object	13 (3)	1	19 (2)	19 (3)	30 (1)
Squeezed, caught	6 (4)	12 (4)	11 (4)	9 (4)	5 (4)
Electricity	4 (5)	3	6 (5)	8 (5)	-
Bumping, crash, collision	2	19 (3)	2	3	-
Overturn	2	4	2	3	-
Explosion, blasting, fire	1	6 (5)	1	1	-
Chemicals	1	0	1	2	-
Total	100	100	100	100	-
Chi square goodness of fit test with study sample	-	$x^2(7) = 54.241$, $p \leq .000$. (Sig.)	$x^2(7) = 14.567$, $p \leq .042$. (Sig.)	$x^2(7) = 27.680$, $p \leq .000$. (Sig.)	-

4.1.1 Distributions of accident types and representativeness

The distribution of injuries on the accident type variable across the samples was evaluated using a chi square goodness of fit test. One requirement for the test is that no more than 20 % of the expected counts are less than five cases. The accident type 'chemicals' was the main contributor to counts less than five and was therefore excluded from the test.

The results show that the study sample was significantly different from the other three samples included in the test. The relations between the other samples were also tested and they were also significantly different from each other. The results clearly indicate that there is a relation between severity and accident types across samples representing different severity. Hence, the main study sample is not completely representative for the fatal injuries or the less severe injuries. However, the order of the accident types is fairly similar to the 'insurance' and 'inspection' samples, while the order of the fatalities is somewhat different. Our assessment is that the study sample is relatively representative for severe injuries. However, we should be cautious about concluding that the shares of the accident types are correct. The results indicate that fall accidents might be overrepresented, and that 'cut' and 'squeezed/caught' might be underrepresented in the study sample. A more thorough comparison of the study sample and sample of fatal injuries is undertaken in section 4.3.

4.2 Construction types and accident types

This section compares the distribution of accident types in the main study across four different construction types. Table 5 describes the construction types and the number of accidents. No data exists for indicating the size of production or working hours for these constructions types, which makes it impossible to produce exposure data. Figure 1 combines construction type and accident type.

Table 5. Construction type and number and per cent of accidents (Typology based on Haslam et al. 2003).

Construction type	Description	N.	%
Building	Residential (houses/apartments) and non-residential (commercial/industrial buildings)	73	41.5
Refurbishment	Refurbishment and renovation	35	19.9
Civil Engineering	Road, rail, bridges, etc.	27	15.3
Engineering Construction	Petro-chemical, power generation, heavy industrial	25	14.2
Other	-	16	9.1
Total	-	176	100.0

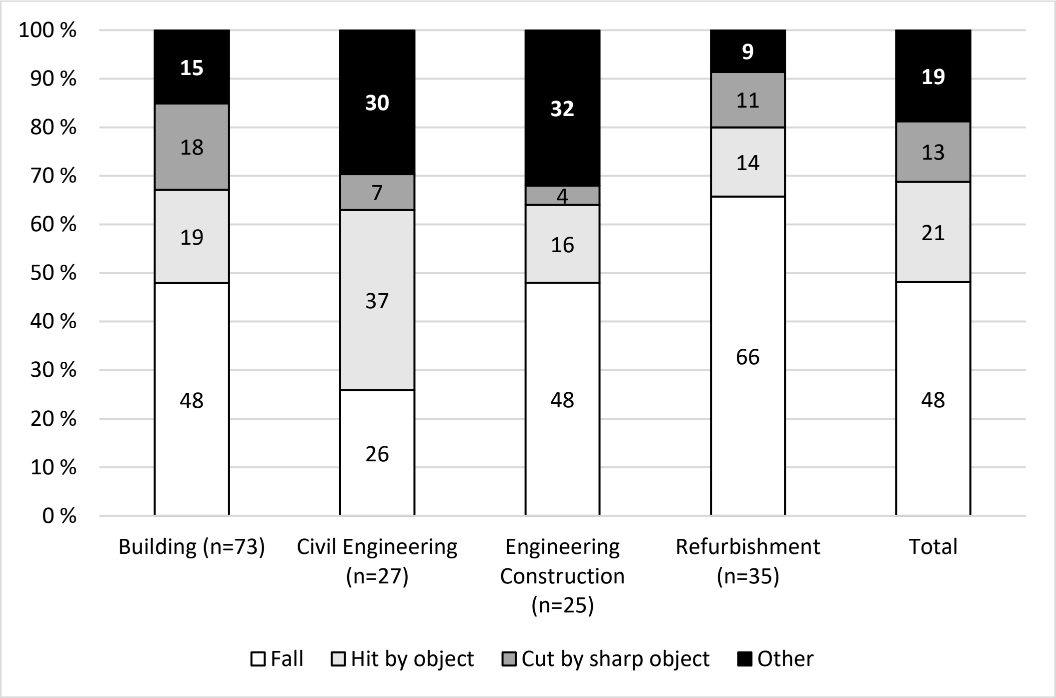

Figure 1. Construction type and accident type combined (n=160). (In 16 accidents, construction type is 'other'). Chi square test: $x^2(9) = 19.747$, $p \leq .002$.

Only the accident types 'fall, 'hit by object', and 'cut' have sufficient observations to be included in the analysis. A chi square test was carried out showing that the distribution of the accident types was significantly different across the four construction types ($x^2(9) = 19.747$, $p \leq .002$). In *Building*, the most frequent accident types are fall from height (roof/floor/platform and scaffold), hit by objects (equipment and materials), and cut by sharp object (mainly saws). The largest difference between *Building* and the other construction types is the relatively high number of 'cut by sharp object'. In *Civil Engineering,* the most frequent accident type is hit by object (mostly heavy objects like concrete slab/block, rocks, poles and plates). The second most frequent accident type is fall from height (scaffolds, platform, lift, beam, and into a hole). Other accidents involved blasting (2), trench collapse (2), and dump trucks (2). *Civil Engineering* has a larger proportion of fatalities/likely fatalities than the other construction types. The results suggest that the hazards involved in *Civil Engineering* accidents are different from the other construction types and that there are often large amounts of energy involved. The accidents in *Engineering Construction* are relatively similar to accidents in *Building*. The main difference being that they happened at other types of sites, for instance industrial sites, warehouses, power plants, and farms. The 12 fall accidents were relatively equally distributed between ladder, scaffold, and roof/floor/platform. In *Refurbishment*, there are many falls from height (66%). 11 of the workers fell through the roof while working on rooftops changing roofing, doing repair work or demolition work. The main triggering factors were that they slipped on the roof and fell, or that the roof collapsed. There were seven falls from scaffolding structures. These accidents mainly happened during refurbishment and/or painting of the front of buildings. The results indicate that the distribution of accidents is relatively different across most construction types.

4.3 Identifying more detailed accident types

This section identifies more detailed 'accident types' by using an accident type variable with 36 different categories developed by the WORM project (Hale et al., 2007). The distribution of accident types in the main study sample is compared to fatal injuries to give a broader basis for prioritisation (Figure 2).

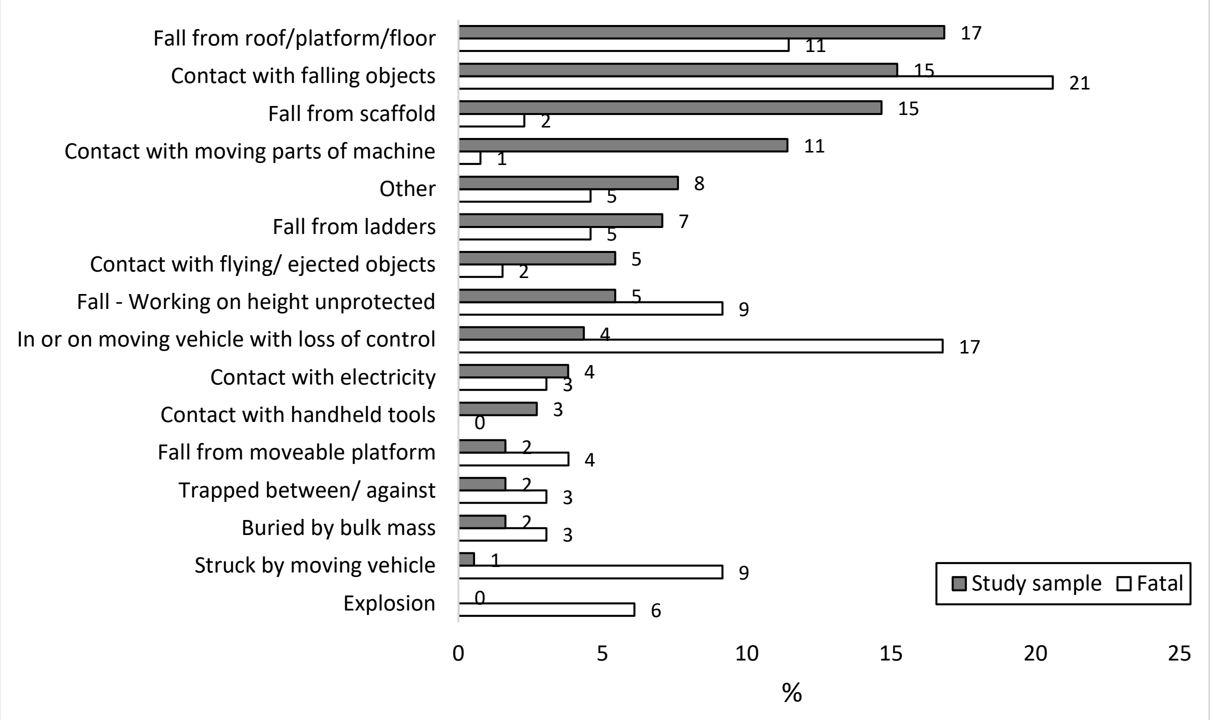

Figure 2. Most frequent accident types (%) for injuries in the study sample (N=184) compared to fatal injuries (2000-2014) (N=131).

A chi square test was carried out for the two samples. To focus on the differences between fatal vs. non-fatal accidents, the four fatal injuries in the study sample were excluded here and included in the sample of fatal injuries in the chi square test. Only 10 types had an expected count of five or more for at least one of the groups (study sample and fatal), and hence 260 injuries were included in the chi square test. The test showed that the distribution of accident types for the study sample and the fatal injuries were significantly different ($x^2(9) = 65.910$, $p \leq .000$). The main difference between the two samples was that many accidents in the main study sample (non-fatal) were related to tools and machines (e.g. saws, angle grinders, and nailing machines), working in height, and flying/ejected objects (e.g. piece of wood or nails), while many of the accident types in the sample of fatal injuries were related to large falling objects (for instance rocks or concrete elements), explosions, and large vehicles. The results show that the differences in accident types between the study sample and fatal accidents can be explained by differences in types of work and type and amount of energy involved.

A list of 7 accident types for prioritisation is suggested and analysed below. The list includes the six most frequent types in Figure 2. 'Contact with flying/ejected objects' was excluded because these accidents included many different types of objects in many different situations, and hence was not an 'incident concentration'. During the analyses, it was found that in 14 accidents, workers were hit by objects during lifting. These accidents were categorised as 'contact with falling objects' (7), 'fall' (4) and 'contact with swinging/hanging objects' (3). This also illustrates that using predefined categories in a mechanistic way might lead to excluding important clusters. It was decided to include 'hit by object in lifting operations' in the analysis despite not being one of 36 categories in the accident type variable. The list of seven accident types applies to severe accidents and are analysed below.

4.4 Analysis of prioritised accident types and barrier failures

In this section, more detailed patterns of scenarios and barrier failures within each of the seven prioritised accident types in the main study sample are identified. The categories of 'central barrier element failures' (Table 6) were developed inductively based on the qualitative descriptions of the accident sequence in the material. The barrier failures are also related to Haddon's (1980) countermeasure strategies (energy barriers) and Trost and Nertney's (1995) barrier limitations. In most of the accidents in this material, there is a lack of sufficient details to assess all of Haddon's strategies related to barrier failures. However, there are sufficient details to assess strategies number four (prevent the release of the hazard), six (separate, in time or space, the hazard and the vulnerable target) and seven (separate by physical barriers). In the discussion of possible measures against the different accident types, all of Haddons' strategies are discussed.

Table 6. The seven accident types and central barrier element failures related to Haddon's strategies (1980) and barrier limitations (N=138 accidents and 169 barrier element failures). (NU=Not used. F=Partial or total failure. NP=Not practical. LE=Latent error. HE=Human error).

Accident type	n.	Central barrier element failures	n.	Haddon	Limitation
	30	Opening/hole in structure	12	7	NU

Fall from roof, floor, platform		Edge protection/fall arrest	9	7	NU
		Floor/roof collapse	4	4	F (LE)
Fall from scaffold	26	Floor deficiency	8	4	F (LE)
		Edge protection/fall arrest	6	7	NU
		Working on the outside of the scaffold or on/under railing	6	7	F (HE)
		Scaffold moving, overturning, collapsing	6	4	F (LE)
Contact with falling objects	25	Workers in the danger zone	25	6	F (HE)
		Objects inadequately attached	12	4	F (HE)
		Loss of control of load/equipment	6	4	F (HE)
		Lifting equipment broke	4	4	F (LE)
Contact with moving parts of a machine	21	Loss of control of saw/material	7	4	F (HE)
		Used hand instead of push stick	4	6	F (HE)
		Worker inattentive and 'bumped into' the blade	4	7	F (HE)
		Condition of saw/saw arrangement inadequate	3	4, 7	NU
Hit by object during lifting	14	Workers in the danger zone	14	6	F (HE)
		Loss of control of the load	7	4	F (HE)
		Edge protection (working in height)	5	7	NU
		Lost control of crane	3	4	F (HE)
		Lifting equipment broke	3	4	F (LE)
Fall from ladder	13	Ladder not attached	10	4	NP
Fall from height – unprotected	9	Unprotected	9	7	NU
Total	138	Total	169	-	-

4.4.1 Fall from height

There were 81 falls from height, representing 46 % of the accidents. The height of the fall was known in 68 of the 81 fall accidents. The average height of the falls was 3.9 metres, the median 2-3 metres, the maximum height 17 metres and the minimum 0.5 metres. 78 % of the fall accidents were between two and five metres. In some of the fall accidents, the injured person fell in two or more stages, and in other accidents the injured person fell into shafts or the like that slowed down the fall. 73 % of the fall accidents were assessed to be likely fatalities if there had been minor changes in the circumstances (one *was* a fatality).

4.4.1.1 Fall from roof, floor, platform

'Openings and holes' were the most frequent barrier failures in fall from roof, floor and platform. The openings were mainly on rooftops, between floors, for ventilation systems, and for staircases. Most of these accidents happened during construction or refurbishment of buildings when there were temporary openings between floors or openings for staircases. Some of the openings were covered with plates etc. that did not support the weight and some plates were not sufficiently attached. In most of these accidents the injured persons were not aware of the openings. ‘Edge protection’ was assessed to be the main barrier failure in nine accidents. Some workers slipped and fell, others got interrupted by another event and took a step aside. In these accidents, no edge protection or fall arrest was implemented. ‘Floor/roof collapse’ was the main barrier failure in four accidents. In two of these accidents, the workers stepped on plates not attached, and in the other two, the workers fell through roof/floor that did not support the weight.

4.4.1.2 Fall from scaffold

‘Floor deficiency’ was the main barrier failure in eight of the scaffold accidents. In four of them, the scaffold floor was in a poor condition (rotten) and in the other four, the scaffold floor was not properly attached and moved when the worker stepped on it. ‘Edge protection’ and ‘fall arrest’ was assessed to be the main barrier failure in six of the scaffold accidents. Some slipped, others ‘forgot’ that there was no protection and took a step aside. ‘Working on the outside of the scaffold, or on/under the railing’ occurred in six accidents. There were physical barrier elements in these situations, but the workers bypassed them. In some accidents, it seems that it was difficult for the workers to do the job standing on the scaffolding so they chose to do it outside or under the railing. ‘Scaffold moving, overturning, or collapsing’ was the main barrier failure in six accidents. Three accidents involved movable scaffolds that were moved while workers stayed on them. In three accidents, the scaffold overturned/collapsed. These six accidents have many dissimilarities and include barrier failures and deviations like moving scaffolds while workers stay on them, deficiencies in attachment, uneven ground, and too much weight on the scaffold so it collapsed.

4.4.1.3 Fall from ladder

In 10 of the accidents involving ladders, the main barrier failure was that the ladders were not properly attached on the top or bottom. In most of the accidents involving a ladder, it would have been safer to use scaffolds, platforms, or lifts. Most of these accidents happened to workers installing, controlling, or taking down electrical systems and heat pumps. These jobs are often short-term jobs where the customer provides the ladder. This group may be especially vulnerable to unsafe working conditions.

4.4.1.4 Fall from height – unprotected

There were nine falls from height where the worker was unprotected, meaning that they were exposed to fall hazard without any physical safety barriers like edge protection, fall arrest equipment, or safety nets. In four of these accidents, the workers were working on structures without any protection (beams and transformer station) where they slipped and fell. In two accidents, the workers were first hit by objects (crane and railing) and then fell.

4.4.1.5 Barrier failures and measures against fall accidents

Many fall accidents are preventable by ‘eliminating the hazard’ (strategy 1). This is often a task for designers and planners. Work at height can be avoided by doing jobs at ground level, for instance assembling edge protection and materials and using extendable tools. Many of the holes, openings, and unprotected edges could have been eliminated. The ‘qualities of the hazard’ (strategy 2) can be reduced by ensuring that there are no items with sharp edges etc. below the workers, and by ‘soft landing systems’. The ‘amount of the hazard’ (strategy 3) can be reduced by lowering the height, reducing the number of workers exposed to fall hazards and the time they are exposed to fall hazards (e.g. job rotation), and reducing the hazardous area (e.g. size of openings and unguarded edges). The ‘release of hazard’ (strategy 4) can be prevented by a ‘work restraint system’ that prevents workers from getting into a fall position, good housekeeping, and by non-slippery surfaces to prevent slips and trips that can lead to falls. ‘Separation in time or space’ (strategy 6) can be achieved by keeping workers out of the fall danger zone when there are temporary openings and areas without edge protection. Some accidents occurred when workers entered scaffolds and platforms during erection, and when altering and disassembling scaffolds and platforms. All fall accidents could have been prevented by adequate physical barriers like edge protection and fall arrest equipment (strategy 7). The workers’ ability to prevent and handle hazardous situations (strategy 8) can be increased by training and recruiting workers that are fit, healthy, experienced, and competent.

4.4.2 Contact with falling objects

Most of the 25 accidents where the workers came in contact with falling objects involved large and heavy objects overturning during construction or deconstruction. Heavy objects include: supporting beam, electricity pole, principal rafter, mesh reinforcement, and concrete wall element (fatal accident). Variation in the size, weight and the height of the fall of the objects influenced the potential of fatality. Most of these accidents were assessed to be *likely* or *possible* fatal accidents, and one *was* fatal.

Large objects exist in most construction projects and hence this hazard is hard to eliminate, modify, or reduce (strategies 1-3). Therefore, preventing release of the hazard (strategy 4) is important. Many of the accidents happened during assembling and disassembling of building structures and materials. In at least 12 of the accidents, the falling objects were inadequately attached. And in at least four of these accidents, strong wind was a triggering factor. A fatal accident happened due to inadequate temporary anchorage of a wall element and strong wind. In these accidents, the injured persons were (of course) in the danger zone (strategy 6). In most of the accidents, the workers did not assess that there was a ‘falling objects hazard’, and hence a danger zone.

4.4.3 Contact with moving parts of a machine

In 21 accidents, the injured persons were in contact with moving parts of a machine. 16 of the accidents involved different types of saw, 10 of them the so-called 'Norsaw'. The injuries in these accidents were mostly loss of fingers or deep cuts in fingers or arms. These are serious injuries, but none of them were assessed to be likely fatalities. In seven of the saw accidents, a kickback or that the piece 'jumped', caused the hand to fall onto the blade.

Hazards related to the saw can be eliminated (strategy 1) by using pre-cut materials. Saw manufacturers produce saws with modified blades and create saws that stop with flesh contact (strategy2). The amount of the hazard (strategy 3) can be reduced by avoiding wearing things that can come in contact with saw, for example, gloves, rings and long sleeves. The release of the hazard can be prevented (strategy 4) by ensuring stability of saw arrangement and materials. In three accidents, inadequacies in the condition of the saw/saw arrangements was found to be a contributing factor. In at least four accidents the injured person used the hand to push the piece of wood and moved the hand into the blade. These accidents could have been prevented by keeping the hand out of the danger zone and using push stick (strategy 6), or by physical barriers like safety guard (strategy 7). Accidents where pieces of wood were thrown from the blade could have been prevented by wearing safety glasses/face shield (strategy 7). In many of the accidents using a saw, the injured persons were young and/or apprentices and inexperienced. And in many, the workers had been doing the same task for a long time. The number of saw accidents can be reduced by recruiting more experienced workers, training, and reducing duration when single workers use the saw to avoid monotonous work (strategy 8).

4.4.4 Hit by object during lifting

During the analyses, it was obvious that accidents where workers were hit by objects during lifting were frequent. However, the type variable has no single category for such accidents. Hence, a free text search for 'crane', 'lifting', and 'hoisting' was carried out, capturing 14 accidents. These were originally categorised as contact with falling objects (7), fall (4), and contact with swinging/hanging objects (3). These 14 accidents involved moving materials or equipment using different types of lifting equipment like cranes, forklift trucks, and excavators.

In some of these accidents, another method for moving the objects could have been used, for instance moving the object by vehicle instead of lifting above ground (strategy 1). In all the lifting accidents, there was a sudden loss of control of the hazard involved (strategy 4). In seven accidents, there was a loss of control of the load. In some of these accidents, the load hit a worker. In others, the worker was trying to unfasten the load when it suddenly loosened and the worker was hit or squeezed. In three accidents, the lifting equipment (hook, strap) broke so that the load/lifting equipment hit the worker. In five accidents, the workers were working at height and were hit by lifted objects and injured in the fall. These are so-called ‘domino accidents’ with successive losses of control (Hale et al., 2007). Edge protection was also a barrier failure in these accidents. Ensuring control of the load and the condition and usability of the lifting equipment is important in preventing release of the hazard in lifting operations (strategy 4).

In all the ‘lifting accidents’, workers were hit by the load, crane, lifting equipment etc., or standing on platform hit by load. A central strategy is to keep workers out of the danger zone and using signallers to ensure that nobody stays in the danger zone (strategy 6).

5 Discussion and conclusion

By studying 176 construction accidents in depth, we aimed to contribute to a more comprehensive knowledge of frequent accident types, barrier failures, and characteristics of construction accidents.

5.1 Accident types

The list of frequent accidents identified in this research adds to the relatively sparse literature on clusters of accident types and barrier failures in the construction industry. It is challenging to compare different studies and statistics on accident types due to use of different accident type variables. However, there seem to be many similarities between this list of frequent accident types and other similar overviews (Ale et al., 2008; Eurostat, 2017; Lipscomb et al., 2000; Swuste et al., 2012). Fall from height dominates in most studies and statistics and other frequent ‘accident types’ are falling/collapsing objects, moving vehicles, moving machine parts, and electricity.

Lists of frequent accident types are important tools for prioritisation. Swuste et al. (2012) concluded (based on a review of studies using mortality data), that there is consensus on a list of the most frequent ‘central events’ in construction between countries. Results presented in this paper, Eurostat accident statistics (Eurostat, 2017), and research by Ale et al. (2008), suggest differences in distribution of accident types for samples representing different severity. The results in this material demonstrated that many of the non-fatal accidents were related to tools and machines, working in height, and flying/ejected objects, while many of the accident types in the sample of fatal injuries were related to large falling objects, explosions, and large vehicles. These differences are explained by differences in the types and amounts of energy involved as described by the energy model (Gibson, 1961; Haddon, 1973). And the differences in the distribution of accident types across construction types identified in this research, is explained by the different types of work, and hence types and amounts of energies involved in the accidents. This has implications for safety management in the construction industry.

The results support arguments that the causes of minor and major accidents are different and that we can not necessarily prevent major accidents by studying and tackling the minor accidents (Hale, 2002; Reason, 1997), or that we cannot prevent minor accidents by studying and tackling major accidents.

5.2 Barrier failures

The analysis of physical barrier failures showed that in some accidents, there were no physical failures identified, only human failures. In many other accidents, there was only *one* physical barrier to keep a specific hazard under control. For instance, when guardrails were missing or the scaffold floor collapsed, there were no other barriers preventing the worker from falling and hitting the ground. Or when the anchoring of a large building element broke, no other barriers were there to prevent the element from falling. In situations with only one physical barrier element, it is of course important that these barrier elements do not fail. Many of these accidents could have been prevented by implementing more than one physical barrier. In many high-risk industries, for instance, the offshore oil and gas industry, the philosophy is that there should be at least two physical barriers in place at all times to prevent a blowout, so called defence-in-depth (Hopkins, 2012; Reason, 1997). The analysis using Haddon's (1980) countermeasure strategies, demonstrated that there were many opportunities for implementing these strategies at different stages in the accident process. The first strategy, to eliminate basic hazards could have been applied in many situations.

Even though many clusters of accident types and barrier failures have been identified in this research, the material demonstrates an abundance of occupational hazards. Jørgensen (2016) describes such hazards as 'simple hazards' that are so common in every work process that most people hardly think about them and have largely learned to deal with them without getting injured. In such settings, it is important to have several different safety barriers for different hazard sources (Bellamy et al., 2010). There is little research on barriers in the construction industry. Priemus and Ale (2010) focused on barriers in accident investigation and Jørgensen et al. (2011) focused on barrier awareness on an individual level. However, systematic establishment and maintenance of barriers can contribute to preventing accidents similar to the ones in this material. Even though there are differences between occupational 'simple hazards' in the construction industry, and hazards in other industries, the construction industry can learn from experience and guidelines for systematic barrier management from other industries (e.g. NPSA, 2017; OGP, 2014).

5.3 Limitations and future research

One strength of the main study sample is that is allows for analysing accident sequences in depth, while one limitation is that the number of accidents is relatively low (N=176). Based on a comparison of the distribution of accident types to other samples of injuries, we assessed that the main study sample can be used to make some generalisations from the sample to relatively severe construction accidents. However, one should be cautious about concluding that the percentages of the accident types are exact. Another limitation with this type of research is that we lack exposure data for the types of work represented by the accident type categories. The frequencies do not indicate risk, only frequencies. A third limitation is that this research focuses primarily on identifying proximal factors in the accident process. Accidents are caused by a complex interaction of latent conditions and active failures (Reason, 1997). The next phase in this research project is to identify how immediate factors are related to shaping and originating factors as described by the Construction Accident Causality framework (Gibb et al., 2014; Haslam et al., 2005).

Acknowledgements

This research is a part of a project about construction safety funded by the Research Council of Norway and the Norwegian Labour Inspection Authority. Its content, conclusions, and the opinions expressed are those of the authors alone. The authors are particularly grateful to Bodil Aamnes Mostue for participating in the data collection and for discussions; to professor Urban Kjellén and Dr. Yogindra Samant for discussions and guidance; and to Ola Opkvitne, Hans Magne Gravseth, and Tore Tynes for participating in the data collection.

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