Performance of barrier systems and functions in the construction industry

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ABSTRACT

Objectives. Improving knowledge about the mechanism of accident occurrence in the construction industry provides important information to help design and implement appropriate barriers to stop the spread of unexpected events. This study characterizes the sequence of accidents in the construction industry by linking the most commonly identified circumstances, the barriers and barrier functions infringed and the specific way in which each of these functioned. *Methods*. In order to achieve the proposed objective, an analysis was made of 241 investigations of work accidents that occurred in the construction sector in Spain between 2009 and 2014. The statistical difference between the groups of variables was determined using contingency tables in which the value of the χ^2 statistic was calculated. *Results*. The results obtained show that behavioural factors are fundamentally identified, such as the worker's non-observance of ensuring their own safety or the deficient interpretation of rules. *Conclusions*. This study illustrates that to understand the performance of barrier systems and functions, efforts must be focused not only on the things that go wrong, i.e., accidents, but also on the things that go right within the variability of daily performance in systems as complex as the construction industry.

KEYWORDS
occupational accidents; construction industry; barrier systems and functions; variable deviation; occupational health and safety

1. Introduction

The construction industry is considered one of the most hazardous industries worldwide when it comes to workers' safety and health [1–3]. In Spain, this is no exception, given that construction is often classified as one of the most accident-prone industries in the country [4,5]. Likewise, when talking about accidents in the construction industry, it is those due to falls from heights that occur most frequently with the most serious consequences, including the death of the injured worker [6–8].

The accident rate in the construction industry is among the highest worldwide compared to other industries or economic sectors [9]. In particular, the analysis of occupational accidents in the construction sector in Spain shows some problematic results. According to the Occupational Accident Rate Statistics of the Ministry of Labour, Migration and Social Security of the Spanish Government [10], the construction sector stands out as the sector with the highest incidence rate of accidents per 100,000 workers per working day compared to the rest of the sectors of economic activity during the period 2007–2018. The worst figure was recorded in 2007, with an incidence rate of 12,393.1 accidents per 100,000 workers. Between 2008 and 2013, there was a gradual decline in this rate as a result of the Spanish economic crisis, which particularly affected the construction sector. After 2013, however, the incidence rate rose to 7982.7 accidents per 100,000 workers in 2018.

These worrying data show the need to gain a better understanding of how accidents in the construction sector develop and from there to design appropriate barriers to stop the spread of unwanted events.

1.1. Review of the literature on the mechanism of accidents in the construction industry

Regarding the mechanism of action of occupational accidents in the construction industry, published studies such as by Arboleda and Abraham [11], Chi et al. [12], Hinze et al. [13], Ale et al. [14], Leung et al. [15], Swuste et al. [16], Carrillo-Castrillo et al. [17], Berglund et al. [18] or Lindgard et al. [19], etc., have tried to identify their main causal associations. The results of these studies showed that the mechanism of accident action in this sector is clearly influenced by the stage of the ongoing process, and that these associations are highly complex and dynamic due to their high probability of exposure to injury.

However, the European Statistics on Accidents at Work (ESAW) [20] do not include accident contributing factors as the main objective of the accident investigation procedure. In this sense, authors such as Kjellén [21], Kjellén and Hovden [22] or Jacinto et al. [23] argue that the coding and identification of the deviation variable is of vital importance, as it establishes in a precise way the previous circumstances in which the accident has occurred. Likewise, studies such as those by Molinero-Ruiz et al. [24] and Jacinto et al. [25] analysed the degree of reliability and validation of the variables used in the notification of occupational accidents in both Spain and Portugal, confirming that the deviation variable is positioned as the easiest to interpret and code.

In relation to the use of the harmonized deviation variable, within the ESAW coding system in the analysis of accidents, the published studies by Antao et al. [26] in the fishing sector in Portugal, by Jacinto et al. [27] in the food industry in the same country, by Carrillo-Castrillo et al. [28] in the manufacturing industry or by Suárez-Cebador et al. [29] in public universities, the latter two in Spain, are noteworthy. However, there are not many bibliographical references in relation to the use of the aforementioned variable in the analysis of accidents in the construction industry. Among them is the study published by López-Arquillos et al. [5] or the one carried out by the European Statistical Office (Eurostat) in 2017 [30]. The former analysed slight, severe and fatal occupational accidents in construction in Spain between 2003 and 2008. The Eurostat study examined fatal accidents at work in the construction industry in Europe in 2015.

1.2. Barrier systems and functions

Regarding the definition, classification and performance of barrier systems and barrier functions, the works of Hollnagel [31], Sklet [32], Hollnagel [33] and Harms-Ringdhal [34] are noteworthy. Despite the absence of a generally accepted definition of this terminology, the review study by Sobral and Guedes-Soares [35] draws attention to the definitions provided by Sklet [32] and Hollnagel [31,33].

According to Sklet [32], while safety barriers are physical and/or non-physical means used to prevent, control or mitigate unwanted events or accidents, the barrier function is one that is actually designed to prevent, control or mitigate unwanted events or accidents. In other words, a barrier system is one that has been designed and implemented to perform one or more barrier functions and may be a combination of these. Hollnagel [33], however, differentiated between what barriers 'do' and what barriers 'are'. Thus, the former situation is the action that the barrier functions perform and the latter is the way in which the barrier function is achieved, i.e., the barrier system itself.

Similarly, there is no consensus on the classification of barrier systems and barrier functions. The categorization and classification of barrier systems can be seen from different perspectives. Thus, we can find classifications according to the origin of the system, according to the role of the system or according to its nature. Regarding the origin of the system, the classification initiated by Johnson [36] and culminated by Kjellén and Albrechtsen [37], which differentiates between physical and non-physical barriers, stands out. In terms of the role of the barrier, the classification by Sklet [32] stands out. This author proposed a categorization between passive or active and physical, technical or human barrier systems. Thirdly, in terms of their nature, we find the classification initiated by Hollnagel in 2004 and later culminated in 2008 [31,33]. This classification was developed into four types: physical or material barrier systems, functional barrier systems, symbolic barrier systems and incorporeal barrier systems.

Hollnagel [33] also proposed a classification that describes how each system operates, i.e., its function. Each of the 17 barrier functions included in this classification was accompanied by at least one practical example of each (see later Table 3). This classification of barrier functions, as Hollnagel himself argues, although not exhaustive, can be considered sufficient to be useful in practice.

After defining and classifying the systems and functions of barriers, in a field analysis of these, it is essential to assess how they act, establishing criteria for their evaluation. In this line and after previous works published by Neogy et al. [38] or Andersen et al. [39], the study by Harms-Ringdhal [34] is noteworthy. This author made a classification of eight parameters for the evaluation of the degree of performance of each barrier function with the aim of identifying the extent to which each one performed adequately during the incident analysed.

On the other hand, according to the published literature, the effect of barrier systems and functions have been extensively studied in specific fields such as civil aviation, nuclear power plants, manufacturing industry, rail transport, electricity distribution or hospitals [35]. However, few published studies have dealt with the analysis of safety barrier systems and functions in the construction sector. The work of Priemus and Ale [40] focused on how barriers act in failed construction projects. Jørgensen et al. [41] identified safety gaps for risk control and accident prevention. More recently, Winge and Albrechtsen [42] in a sample of 176 accidents in the Norwegian construction industry identify the most frequent types of accidents and the elements of failed control barriers.

1.3. Scope and contribution of this research

In view of the aforementioned, the aim of the study presented here, based on the analysis of a sample of 241 occupational accidents in the construction sector in Spain, is to characterize the sequence of accidents occurring in this sector. This goes beyond simple knowledge of the circumstances of the accident. In this sense, in each accident investigation report, the system and function of the safety barrier infringed were considered, establishing a relationship between the most common deviations that occur with the safety barriers that fail to a greater extent. It was also analysed whether or not the safety barriers served their purpose adequately, either because they did not exist or because they malfunctioned.

The first step in the proposal of this study is to determine which deviation variable is identified as a circumstance in the highest percentage of occupational accidents in the construction sector. Secondly, it is to classify which barrier systems are infringed to a greater extent in the accidents analysed in relation to the identified deviation variable. The third proposal is to find out to what extent each of the identified barrier functions works or not, i.e., to understand the degree to which it works. These proposals make it possible to obtain useful information that can serve as a basis for the various stakeholders to formulate strategies to focus efforts and limit the serious consequences of the accidents under consideration.

This study is therefore expected to be beneficial to the researchers of system and safety engineering, with systematically streamlining and innovatively categorizing the recent findings and insights.

After putting the subject matter and objectives into context in this Introduction, the rest of the document is structured as follows. Section 2 is devoted to explaining the sample of accident investigation reports used, as well as describing the methodology-based approach. In terms of methodology, the classification of deviations into accidents, systems and barrier functions is detailed, together with the performance of the latter. Section 3 presents the results obtained and Section 4 includes the discussion of the main results, the article ending with conclusions and guidelines for future research in Section 5.

2. Materials and methodology

2.1. Study samples

The study presented here is based on the results of the analysis of 241 investigation reports of occupational accidents

Table 1. Distribution of reports analysed.

Variable	Category	No. of reports (%)
Organization mode	Internal OHS advisors	103 (42.7)
	External OHS advisors	138 (57.3)
Accident seriousness	Slight	188 (78)
	Severe	44 (18.3)
	Very severe	1 (0.4)
	Fatal	8 (3.3)
Contract/subcontract	Contract	169 (70.1)
	Subcontract	72 (29.9)
Total	–	241 (100)

Note: OHS = occupational health and safety.

that occurred in Spain between 2009 and 2014, which were carried out by occupational safety technicians from private companies (hereinafter occupational health and safety [OHS] technical advisors, whether internal or contracted to external consultancies).

The 241 investigation reports analysed are classified as presented in Table 1, according to the organizational modality (OHS) of the company where the injured worker worked, the degree of severity of the accident and whether the company for which the injured worker worked acted as a main contractor or a subcontractor.

2.2. Classification of deviation in accidents

We then proceeded to identify the variable deviation in each of the 241 accident investigation reports for accidents in the construction sector, either because it is explicitly indicated or after reading the reports. The coding for the deviation variable in each of the investigation reports was carried out according to the procedure harmonized in the ESAW methodology [43] (see Table 2).

2.3. Barrier systems

In Spain, the procedures for the completion of accident investigation reports do not include the identification of barrier systems and functions. Therefore, the next step was to identify the barrier system infringed in each accident by reading through each of the investigation reports in the sample.

The classification of types of barrier systems established by Hollnagel [33] into four categories was used as follows:

- physical or material barrier system – a barrier that prevents an event from occurring or mitigates the effects by blocking the transport of mass, energy or information from one location to another;
- functional barrier system – a barrier that creates one or more preconditions that must be met before an action can be carried out;
- symbolic barrier system – a barrier that functions indirectly through its meaning, which requires interpretation by someone;
- incorporeal barrier systems – a non-physical barrier which depends on the user's knowledge and is often organizationally related.

Also, as Hollnagel [33] himself maintains, barriers are often based on a combination of barrier systems. This is why the analysis of the sample of 241 accident reports identified the existence or not of a combined barrier system.

Similarly, a paragraph was added for those investigation reports that 'did not expressly identify' the existence of a barrier system included in the aforementioned classification.

Each of the barrier systems identified were associated with the deviation variable for each of the 241 accidents analysed.

2.4. Barrier functions

Subsequently, as in the previous section and continuing with the complete review of the sample used, for each barrier system infringed, the specific manner in which each barrier achieved its purpose, i.e., its barrier function, was identified.

As with barrier systems, Hollnagel's [31,33] classification was used for the identification of barrier functions (see Table 3).

2.5. Performance of barrier functions

The extent to which each of the identified barrier functions worked or did not work was then assessed. In order to make this assessment of the performance of the barrier functions as systematic and consistent as possible, the classification by Harms-Ringdhal [34] into seven groups was used (see Table 4).

2.6. Statistical analysis

After collection and examination, the data were tabulated and statistically analysed by computer, using Microsoft 365 and SPSS version 25.0.

In order to test the possible correlation between the factors analysed, different hypotheses were proposed and studied using non-parametric tests. On the one hand, it was analysed whether the deviation variable identified as an accident circumstance in each of the reports was related to the barrier system infringed. For this, the deviation variable was grouped around groups 00–99 presented in Table 2 and the barrier systems according to the classification presented in Table 3 (physical, functional, symbolic and incorporeal barrier systems). To the latter are added those reports that identify a barrier system resulting from the combination of the four indicated as being infringed, as well as all research reports that do not identify the system infringed.

In addition, another correlation was explored. In this case, the aim was to analyse whether the specific way in which each of the barrier systems achieved its purpose, i.e., the barrier function, was related to the degree of performance of each of these functions. To this end, the barrier function variable was selected according to the classification presented in Table 3 and the performance of each barrier function according to the classification presented in Table 4.

The study of the relationship between the groups of variables indicated was carried out using contingency tables in which the value of the χ^2 statistic was calculated to test the hypothesis of independence of severity with respect to the variables [4,5]. This statistic shows the possible influence of the different values of the variables studied.

3. Results

3.1. Distribution of the variable deviation

In response to the first proposal made for this study, Table 5 presents the analysis of the ESAW variable 'deviation' of the

Table 2. Variable deviation coding.

Group Label
00 No information
10 Deviation due to electrical problems, explosion, fire – not specified
11 Electrical problem due to equipment failure – leading to indirect contact
12 Electrical problem – leading to direct contact
13 Explosion
14 Fire, flare up
19 Other group 10-type deviations not listed above
20 Deviation by overflow, overturn, leak, flow, vaporization, emission – not specified
21 Solid state – overflowing, overturning
22 Liquid state – leaking, oozing, flowing, splashing, spraying
23 Gaseous state – vaporization, aerosol formation, gas formation
24 Pulverulent material – smoke generation, dust/particles in suspension/emission of
29 Other group 20-type deviations not listed above
30 Breakage, bursting, splitting, slipping, fall, collapse of material agent – not specified
31 Breakage of material – at joint, at seams
32 Breakage, bursting – causing splinters (wood, glass, metal, stone, plastic, others)
33 Slip, fall, collapse of material agent – from above (falling on the victim)
34 Slip, fall, collapse of material agent – from below (dragging the victim down)
35 Slip, fall, collapse of material agent – on the same level
39 Other group 30-type deviations not listed above
40 Loss of control (total or partial) of machine, means of transport or handling equipment, hand-held tool, object, animal – not specified
41 Loss of control (total or partial) – of machine (including unwanted start-up) or of the material being worked by the machine
42 Loss of control (total or partial) – of means of transport or handling equipment (motorized or not)
43 Loss of control (total or partial) – of hand-held tool (motorized or not) or of the material being worked by the tool
44 Loss of control (total or partial) – of object (being carried, moved, handled, etc.)
45 Loss of control (total or partial) – of animal
49 Other group 40-type deviations not listed above
50 Slipping – stumbling and falling – fall of persons – not specified
51 Fall of person – to a lower level
52 Slipping – stumbling and falling – fall of person – on the same level
59 Other group 50-type deviations not listed above
60 Body movement without any physical stress (generally leading to an external injury) – not specified
61 Walking on a sharp object
62 Kneeling on, sitting on, leaning against
63 Being caught or carried away, by something or by momentum
64 Uncoordinated movements, spurious or untimely actions
69 Other group 60-type deviations not listed above
70 Body movement under or with physical stress (generally leading to an internal injury) – not specified
71 Lifting, carrying, standing up
72 Pushing, pulling
73 Putting down, bending down
74 Twisting, turning
75 Treading badly, twisting leg or ankle, slipping without falling
79 Other group 70-type deviations not listed above
80 Shock, fright, violence, aggression, threat, presence – not specified
81 Shock, fright
82 Violence, aggression, threat – between company employees subjected to the employer's authority
83 Violence, aggression, threat – from people external to the company toward victims performing their duties (bank hold-up, bus drivers, etc.)
84 Aggression, jostle – by an animal
85 Presence of the victim or of a third person in itself creating a danger for oneself and possibly others
89 Other group 80-type deviations not listed above
99 Other deviations not listed above in this classification

Source: Eurostat [43].

sample of 241 occupational accident investigation reports in the construction sector.

As can be seen, the predominant frequency rate of deviation is group 51 'Fall of person – to a lower level' with 18.7% of cases, exceeding group 52 'Slipping – stumbling and falling – fall of person – on the same level' by almost twice as many cases with 10.4% and group 71 'Lifting, carrying, standing up' with 10%.

If we analyse by group, we can see that almost one out of every three accidents analysed occurs as a result of a 'Slipping – stumbling and falling – fall of persons – not specified' (group 50). Group 40, which includes 'Loss of control (total or partial)

Table 3. Barrier functions for the four barrier systems.

Barrier system	Barrier function	Example
Physical	Contain or protect. Prevent transporting something from the present location (release) or into another (intrusion) Restrain or prevent movement or transportation of mass or energy Keep together. Cohesion, resistance Separate, protect, block	Walls, doors, buildings, restricted physical access, railings, fences, filters, containers, tanks, valves, rectifiers, etc. Safety belts, harnesses, fences, cages, spatial distance (gulfs, gaps), etc. Components that do not break easily (safety glass) Crumble zones, scrubbers, filters, etc.
Functional	Prevent movement or action (mechanical, hard) Prevent movement or action (logical, soft) Hinder or impede actions (spatio-temporal) Dampen, attenuate Dissipate energy, quench, extinguish	Locks, equipment alignment, physical interlocking, equipment match, etc. Passwords, entry codes, action sequences, pre-conditions, physiological matching, etc. Distance, persistence, delays, synchronization, etc. Active noise reduction, active suspension Air bags, sprinklers, etc.
Symbolic	Counter, prevent or thwart actions (visual, tactile interface design) Regulate actions Indicate system status or condition (signs, signals and symbols) Permission or authorization (or the lack thereof) Communication, interpersonal dependency	Coding of functions, demarcations, labels and warnings (static), etc. Instructions, procedures, dialogues, etc. Signs (e.g., traffic signs), signals (visual, auditory), warnings, alarms, etc. Work permit, work order Clearance, approval, (online or offline), in the sense that the lack of clearance, etc., is a barrier
Incorporeal	Comply, conform to monitor, supervise Prescribing: rules, laws, guidelines, prohibitions	Self-restraint, ethical norms, morals, social or group pressure Control (by itself or by another) Rules, restrictions, laws (all either conditional or unconditional), etc.

Source: Hollnagel [31,33].

Table 4. Classification of barrier function performance.

Code	Description
a	Yes, the barrier function was in place and performed satisfactorily
b	Partly, the barrier function worked to some extent but not completely
c	No, the barrier function did not perform as expected
d	Suggested; the barrier function did not exist and emanates from a suggested improvement
e	Counter-effect; the barrier function increased risk in some way
f	Unclear; performance was uncertain
g	The barrier function was not related to the incident

Source: Harms-Ringdahl [34].

of machine, means of transport or handling equipment, hand-held tool, object, animal – not specified', is a distant second with 26.2% of the cases. As can be seen, groups 50, 40 and 70 account for 73% of the total number of cases analysed.

3.2. Distribution of barrier systems infringed by deviation

Table 6 presents the overall distribution of barrier systems identified as infringed in the sample of 241 construction accident reports.

As can be seen, the incorporeal barrier system is the most prevalent with 24.9% of cases. It is worth noting that 32% of the sample analysed did not identify the barrier system infringed.

Next, and continuing with a detailed reading of each of the accident investigation reports, an association is made between the deviation variable of each accident and the barrier system identified as having been infringed. As presented in Table 7, of the barrier systems identified, the physical barrier associated with deviation group 50 'Slipping – stumbling and falling – fall of persons – not specified' is the one with the highest percentage of infringements (9.5% of cases). With regard to deviation group 50, the falls suffered by injured workers are due to the absence or malfunctioning of physical barriers such as collective protection (guardrails, scaffolding) or individual protection (safety belts or harnesses).

In second place is the incorporeal barrier system with 7.1% of cases, associated with both deviation group 50 and group 40 'Loss of control (total or partial) of machine, means of transport or handling equipment, hand-held tool, object, animal – not specified'. Among these incorporeal barrier systems, some stand out as infringements, such as the lack of control by oneself or by others of the tasks performed, as well as non-compliance with the rules established in the workplace.

In third place is the symbolic barrier system with a percentage of 6.3% associated with deviation group 40. Within this category of barrier systems, among the symbolic barriers as infringed are those for the signposting of the different pits or the absence of written procedures for carrying out the different tasks assigned.

The remaining infringed barrier systems associated with the nine groups of deviation variables are identified at values below 4%.

The statistical correlation analysis performed between the deviation variable identified as a circumstance in the sample of accident investigation reports with the barrier system infringed shows that there is no statistically significant association ($\chi^2 = 30.581$; $p = 0.166$; $df = 24$; contingency coefficient $= 0.404$).

3.3. Distribution of barrier functions by systems and their performance

Next, an attempt is made to answer the third proposal of this research, regarding to what extent each of the identified barrier functions worked or not. To this end, as presented in Table 8, a relationship is made between the barrier systems infringed, the specific way in which each of these barrier systems function [33] and the degree of performance of each of these functions according to the classification made by Harms-Ringdhal [34].

As can be seen from Table 8, of the 172 barrier systems identified as being infringed in the sample of construction accidents analysed, the barrier function with the highest percentage of infringes is 'comply or conform to' with 26.1%. In second place is the function 'Restraint or prevent movement', which is infringed in 22.1% of cases. In third place is the function 'regulate actions' with 19.2%.

Table 5. Distribution of deviation variables.

Deviation (ESAW) group	*n* (%)	Deviation subgroup	*n* (%)
50 Slipping – stumbling and falling – fall of persons – not specified	70 (29)	51 Fall of person – to a lower level	45 (18.7)
		52 Slipping – stumbling and falling – fall of person – on the same level	25 (10.4)
40 Loss of control (total or partial) of machine, means of transport or handling equipment, hand-held tool, object, animal – not specified	63 (26.2)	41 Loss of control (total or partial) – of machine (including unwanted start-up) or of the material being worked by the machine	14 (5.9)
		42 Loss of control (total or partial) – of means of transport or handling equipment (motorized or not)	9 (3.7)
		43 Loss of control (total or partial) – of hand-held tool (motorized or not) or of the material being worked by the tool	19 (7.9)
		44 Loss of control (total or partial) – of object (being carried, moved, handled, etc.)	20 (8.3)
		49 Other group 40-type deviations not listed above	1 (0.4)
70 Body movement under or with physical stress (generally leading to an internal injury) – not specified	43 (17.8)	71 Lifting, carrying, standing up	24 (10)
		72 Pushing, pulling	1 (0.4)
		73 Putting down, bending down	6 (2.5)
		74 Twisting, turning	2 (0.8)
		75 Treading badly, twisting leg or ankle, slipping without falling	9 (3.7)
		79 Other group 70-type deviations not listed above	1 (0.4)
60 Body movement without any physical stress (generally leading to an external injury) – not specified	28 (11.7)	63 Being caught or carried away, by something or by momentum	18 (7.5)
		64 Uncoordinated movements, spurious or untimely actions	9 (3.7)
		69 Other group 60-type deviations not listed above	1 (0.4)
30 Breakage, bursting, splitting, slipping, fall, collapse of material agent – not specified	18 (7.5)	31 Breakage of material – at joint, at seams	1 (0.4)
		32 Breakage, bursting – causing splinters (wood, glass, metal, stone, plastic, others)	2 (0.8)
		33 Slip, fall, collapse of material agent – from above (falling on the victim)	5 (2.1)
		34 Slip, fall, collapse of material agent – from below (dragging the victim down)	4 (1.7)
		35 Slip, fall, collapse of material agent – on the same level	4 (1.7)
		39 Other group 30-type deviations not listed above	2 (0.8)
20 Deviation by overflow, overturn, leak, flow, vaporization, emission – not specified	12 (5)	21 Solid state – overflowing, overturning	1 (0.4)
		22 Liquid state – leaking, oozing, flowing, splashing, spraying	5 (2.1)
		23 Gaseous state – vaporization, aerosol formation, gas formation	1 (0.4)
		24 Pulverulent material – smoke generation, dust/particles in suspension/emission of	4 (1.7)
		29 Other group 20-type deviations not listed above	1 (0.4)
10 Deviation due to electrical problems, explosion, fire – not specified	3 (1.2)	11 Electrical problem due to equipment failure – leading to indirect contact	2 (0.8)
		19 Other group 10-type deviations not listed above	1 (0.4)
80 Shock, fright, violence, aggression, threat, presence – not specified	3 (1.2)	81 Shock, fright	1 (0.4)
		83 Violence, aggression, threat – from people external to the company toward victims performing their duties (bank hold-up, bus drivers, etc.)	1 (0.4)
		85 Presence of the victim or of a third person in itself creating a danger for oneself and possibly others	1 (0.4)
00 No information	1 (0.4)	00 No information	1 (0.4)
Total	241 (100)	–	241 (100)

Note: ESAW = European Statistics on Accidents at Work [20].

Table 6. Distribution of barrier systems infringed.

System barrier	*n*	%
Physical	58	22.9
Functional	11	4.3
Symbolic	39	15.4
Incorporeal	63	24.9
Combined	1	0.4
Not identified	81	32
Total	253	100

But in response to the third research proposal asking to what extent the identified barrier functions work, it is noteworthy that 41.27% of the barrier functions 'did not perform as expected' (code c) and even 37.21% simply did not exist (code d) and were included in the research report as a suggested improvement after the accident.

The statistical correlation analysis carried out between the barrier function variable and the variable measuring the degree of performance of each of these functions shows that there is a statistically significant association between the two

Table 7. Distribution of barrier systems infringed by deviation.

Deviation (ESAW) group	*n* (%)	Barrier system infringed	*n* (%)
50 Slipping – stumbling and falling – fall of persons – not specified	70 (29)	Physical	24 (9.5)
		Functional	2 (0.8)
		Symbolic	10 (3.9)
		Incorporeal	18 (7.1)
		Not identified	27 (10.7)
40 Loss of control (total or partial) of machine, means of transport or handling equipment, hand-held tool, object, animal – not specified	63 (26.2)	Physical	11 (4.3)
		Functional	4 (1.6)
		Symbolic	16 (6.3)
		Incorporeal	18 (7.1)
		Not identified	14 (5.5)
70 Body movement under or with physical stress (generally leading to an internal injury) – not specified	43 (17.8)	Physical	5 (1.9)
		Functional	2 (0.8)
		Symbolic	1 (0.4)
		Incorporeal	8 (3.1)
		Not identified	26 (10.3)
60 Body movement without any physical stress (generally leading to an external injury) – not specified	28 (11.7)	Physical	4 (1.6)
		Functional	1 (0.4)
		Symbolic	6 (2.4)
		Incorporeal	9 (3.5)
		Not identified	9 (3.5)
30 Breakage, bursting, splitting, slipping, fall, collapse of material agent – not specified	18 (7.5)	Physical	5 (1.9)
		Functional	1 (0.4)
		Symbolic	3 (1.2)
		Incorporeal	7 (2.7)
		Not identified	4 (1.6)
20 Deviation by overflow, overturn, leak, flow, vaporization, emission – not specified	12 (5)	Physical	8 (3.1)
		Functional	1 (0.4)
		Incorporeal	2 (0.8)
		Combined	1 (0.4)
10 Deviation due to electrical problems, explosion, fire – not specified	3 (1.2)	Physical	1 (0.4)
		Symbolic	2 (0.8)
80 Shock, fright, violence, aggression, threat, presence – not specified	3 (1.2)	Incorporeal	1 (0.4)
		Not identified	1 (0.4)
00 No information	1 (0.4)	Symbolic	1 (0.4)
Total	241 (100)	–	253 (100)

Note: ESAW = European Statistics on Accidents at Work [20].

variables ($\chi^2 = 379.512$; $p = 0.000$; $df = 98$). Furthermore, a statistically significant and directly proportional relationship was found (contingency coefficient = 0.773; $p < 0.05$).

4. Discussion

According to the results obtained, there seem to be many similarities between the most frequent deviations identified in this research and the data extracted from the Ministry of Labour, Migration and Social Security of the Government of Spain. In relation to the statistics of the Ministry of Labour, Migration and Social Security [10], the distribution of the deviation variable in the construction sector in the total number of occupational accidents with sick leave in Spain between 2014 and 2018 shows that group 40 'Loss of control (total or partial) of machine, means of transport or handling equipment, hand-held tool, object, animal – not specified', group 50 'Slipping – stumbling and falling – fall of persons – not specified', group 60 'Body movement without any physical stress (generally leading to an external injury) – not specified' and group 70 'Body movement under or with physical stress (generally leading to an internal injury) – not specified' of the analysed deviation variable are the most frequently identified. Therefore, in the total number of accidents with sick leave in Spain in the construction sector between 2014 and 2018, these four groups account for 82.51% of the total, while in the analysis of the sample used in this study of 241 accident investigation reports analysed in the same sector between 2009 and 2014, these same four groups of the deviation variable account for 84.70%. Figure 1 illustrates the total number of lost-time accidents comparatively between the two studies .

Similarly, the results put the focus on the deviation group 40 'Loss of control (total or partial) of machine, means of transport or handling equipment, hand-held tool, object, animal – not specified' and group 50 'Slipping – stumbling and falling – fall of persons – not specified', as they are identified in more than half of the accidents in construction. This situation was already obtained in the research by López-Arquillos et al. [5] conducted on a total of 1,163,178 accidents that occurred in the period between 2008 and 2012, and by Eurostat [30] conducted on a total of 619 fatal accidents at work in the construction industry in the 23 EU Member States in 2015.

In relation to the systems and functions of barriers, the results show that in the predominant circumstance of

Table 8. Distribution of infringed barrier systems, barrier functions and their performance.

Barrier system infringed	*n* (%)	Barrier function	*n* (%)	Barrier function performance code						
				a	b	c	d	e	f	g
Physical	58 (33.7)	Constrain or protect	15 (8.7)	1	2	4	7	1	0	0
		Restrain or prevent	38 (22.1)	0	1	16	20	0	1	0
		Keep together	3 (1.7)	0	1	2	0	0	0	0
		Separate, protect, block	2 (1.2)	0	0	1	1	0	0	0
Functional	11 (6.4)	Prevent movement or action (mechanical, hard)	3 (1.7)	0	0	1	2	0	0	0
		Prevent movement or action (logical, soft)	5 (2.9)	0	0	2	2	0	0	1
		Hinder or impede actions (spatio-temporal)	3 (1.7)	0	0	1	1	0	1	0
Symbolic	39 (22.7)	Regulate actions	33 (19.2)	0	1	17	9	2	4	0
		Indicate system status or condition	4 (2.3)	0	0	0	4	0	0	0
		Permission or authorization	1 (0.6)	0	1	0	0	0	0	0
		Communication, interpersonal dependency	1 (0.6)	0	0	0	1	0	0	0
Incorporeal	63 (36.6)	Comply, conform to	45 (26.1)	0	1	18	10	0	14	2
		Monitoring supervision	11 (6.4)	0	1	5	5	0	0	0
		Prescribing	7 (4.1)	0	0	3	2	0	2	0
Combined	1 (0.6)	–	–	–	–	1	–	–	–	–
Total	172 (100)	–	171 (100)	1	8	71	64	3	22	3

Note: Codes a–g are codes of classification of barrier function performance (see Table 4). The full list of codes is published in English by Harms-Ringdhal [34].

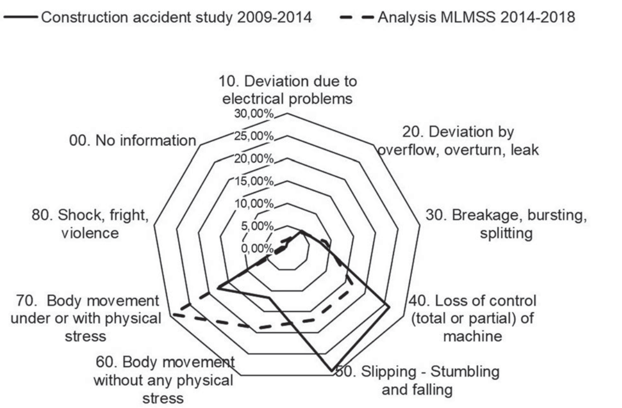

Figure 1. Ministerio de Trabajo Migraciones y Seguridad Social del Gobierno de España.

accidents in construction, such as the fall of the worker, especially at height, the most commonly infringed barrier system is the physical or material barrier. In the construction industry, collective protection systems, such as guardrails, safety nets, etc., can be considered as physical barriers [44]. However, from the analysis of the barrier functions associated with physical systems, it can be deduced that in two out of three cases it is due to the absence of a system that restricts or prevents movement. This may be due to inadequate or even non-existent use of personal protective equipment (PPE) such as safety belts or harnesses [45,46]. However, fall protection measures such as safety belts and harnesses are considered to be the last barrier to prevent injuries.

Likewise, it is worth noting that in terms of symbolic barrier systems, those functions aimed at regulating actions such as instructions or procedures are clearly predominant as infringed. This type of barrier system as discussed by Hollnagel [31,33] is certainly widespread in a modern society, requiring cognitive interpretation by an individual in order to fulfil its purpose.

However, it is quite remarkable that more than one out of three barrier systems identified as infringed were incorporeal. The barrier function was associated with a lack of self-control or lack of compliance with ethical, moral or social pressure norms. It is questionable whether this situation is due to possible safety-related behaviours of the construction workers themselves [47,48].

Ultimately, the analysis of the barrier systems and functions infringed shows that behavioural factors such as the worker's failure to look after his or her own safety or poor interpretation of rules are identified as the main factors. It can also be attributed to group or social pressure, such as time saving or production stress. This is confirmed by studies such as by Winge and Albrechtsen [42] and Lim et al. [8]. Consequently, as argued by Rasmussen [49]: 'The boundary of safe behaviour of one particular actor depends on the possible violation of defences by other actors' (183).

On the other hand, the analysis of the performance of the barrier functions according to the methodology proposed by Harms-Ringdhal [34] gives us a discouraging result. This is either because 41.27% of the barrier functions did not work as expected or because 37.21% did not exist and emanated from an improvement suggested after the accident. This could be due to the fact that the analysis was carried out on a sample of accidents rather than incidents or near-accidents where the contributory factors may be interrupted before injuries occur. Even with a majority sample (78% of cases) of slight accidents, the challenge is to reduce the frequency of severe accidents. Therefore, as stated by Swuste et al. [50], methods must be developed that facilitate the automatic assessment of the progression of accident scenarios and the degradation of the barrier over time.

It is also necessary to establish the differences between safety barriers and countermeasures. Within the bow-tie metaphor [16] representative of the accident process, the intervention of a barrier occurs to reduce or eliminate losses. This is why it is recognized that failed safety barrier systems are related to the strategy in terms of the preventive measures or countermeasures that are proposed [51]. So, while barrier systems are physical or non-physical means to ensure that an accident does not occur [32], preventive measures are recommendations to prevent or control problems identified in the accident that have already occurred [23,52,53].

At present, the new paradigm in health and safety management is resilience engineering [54]. Resilience engineering considers that normal performance is subject to variability and that variability is necessary for success and should not be constrained. The conceptual model developed under resilience engineering breaks with the traditional reactive safety concept focused on studying things that go wrong by analysing simple causal relationships coined with the term Safety-I [55]. In the current framework is the proactive approach called Safety-II, which aims to go further by studying things that go right and day-to-day success through complex and non-linear relationships.

Having said that, and under the resilience engineering paradigm within construction health and safety, the performance and functions of barrier systems must play an essential role in preventing failure and mitigating the consequences by withstanding system disruption. Thus, if one barrier fails in a system, another barrier should be implemented to stop the propagation of the failure, thereby restoring system performance to a relatively high level.

5. Conclusions

The aim of this study was to characterize the sequence of accidents in the construction sector by establishing a relationship between the circumstances mostly identified, the barriers and barrier functions infringed, as well as the specific way in which each of these functioned.

In the context of the construction industry, different safety systems and functions are generally identified and often even overlap. Sometimes they function as redundant safety elements, which makes the system less vulnerable to changes and supports the preservation of safety.

This study concludes that although the infringement of a safety barrier is rarely the cause of an accident, improving the knowledge gained about the mechanism of performance in the construction industry provides important information that helps to design and implement appropriate barriers to stop the propagation of unexpected events. Yet we understand that to comprehend the performance of barrier systems and functions we must focus our efforts not only on the things that go wrong, i.e., accidents, but also on the things that go right within the variability of daily performance in systems as complex as construction.

Indeed, as Herrera and Woltjer [56] argue, it is necessary to have barriers that not only prevent undesirable events, but also protect against their consequences. In short, barrier systems and their functions should be both barriers to and facilitators of variability.

Finally, we believe that it would be essential to carry out a classification of barrier systems and functions exclusively for the construction sector, this being an area of future research of interest. Such a classification would be made for the most frequent or common accidents encountered on construction sites. It would also be essential to include a set of practical examples to aid understanding and implementation. In the same way, it should incorporate information on the regulations or prescribed legislation that has not been complied with that supports the system or function of the incorporeal barrier infringed according to the case in question. All of this would result in a reduction of subjectivity and an improvement in the effectiveness of the choice of safety barrier.

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Ethics approval

All subjects gave their informed consent for inclusion before they participated in the study. The study was conducted in accordance with the Declaration of Helsinki.

Disclosure statement

No potential conflict of interest was reported by the authors. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this article.

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