Causes, Solutions, and Adoption Barriers of Falls from Roofs in the Singapore Construction Industry

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Abstract: Fall from roof (FFR) has been a perennial problem in the construction industry. It has been one of the leading sources of injuries and accidents in many countries. The objectives of this paper are to (1) investigate the causes of fall from roof; (2) identify control measures to roof safety that are being used in the Singapore construction industry; (3) evaluate these controls based on specific working on roof scenarios; and (4) investigate factors that influence the adoption of these solutions. Eleven semi-structured interviews were conducted with experienced practitioners in the Singapore construction industry. In addition, two focus group discussions were conducted to discuss fall protection solutions for six critical and common working on roof scenarios identified during the interviews. Results suggested that FFR accidents and injuries were caused by a combination of individual and organizational factors. Cost-effectiveness, workers competency, and site constraints are the most critical factors that differentiate solutions to specific roofing scenarios. Despite the existing solutions, it was found that some contractors are reluctant to implement appropriate solutions in their roof work due to (1) cost; (2) time pressure; (3) power imbalance; and (4) on-site constraints. Based on these findings, it was suggested that establishing a roof association would help reduce FFR accidents and injuries by addressing the following issues: (1) design working-on-roof best practices; (2) improve tendering process; and (3) develop and manage a licensing roofing worker program. **DOI: 10.1061/(ASCE)CO.1943-7862.0001649.**

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Introduction

Fall from heights (FFH) has been a major contributor toward both minor and major work-related injuries in the construction industry of many countries and regions, such as Singapore (WSHC 2016), UK (HSE 2015), US (Bobick 2004), and Hong Kong (Wong et al. 2016). For example, FFH accounted for over 20% of the major injuries in Singapore workplaces over the past five years. Among all FFH cases, fall from roof (FFR) has been one of the leading sources of injuries and accidents (Fredericks et al. 2005; HSE 2012; Safe Work Australia 2013; WSHC 2016). Working on a roof is highly risky as workers can fall from the edges of a roof or through gaps, holes, and fragile roof materials. The likelihood of a roofer to experience a fatal occupational injury such as falling from height is three times higher as compared to a normal construction worker (Dong et al. 2013). During the period between 1994 and 2000 in the US, the fatality rate for roofers caused by falling is 4.5 times the fatality rate for all construction workers caused by falling. 359 workers were killed by fall from height in Australia between 2003 and 2015 and the leading source of these fatalities was falling from roofs (Safe Work Australia 2015).

Over the past three decades, research efforts have been made to identify risk factors and root causes of FFR accidents and injuries (Bobick 2004; Johnson et al. 1998; Kines 2002; Moore and Wagner 2014). Different fall protection equipment and systems were evaluated (Bobick et al. 2010; Goh and Wang 2015; Lan and Galy 2016). In the meantime, a number of working-at-height (WaH) standards and best-practices were developed to support employers and workers to select and implement proper fall protection solutions. Despite these efforts, there is a lack of a comprehensive study which investigates the relationship between both safety knowledge and motivation issues at different levels (e.g., worker, supervisor, company, owner, training provider, and the government). It is unclear why employers did not adopt required fall protection tools and equipment. The importance of workers' WaH knowledge has been highlighted for decades. It is, however, not clear that why it still remains a significant issue today in the construction industry. To reduce falls requires a deeper understanding of why workers fall, what solutions are being used, and why people (do not) select these solutions.

Thus, the objectives of this paper are: (1) investigate the causes of fall from roof; (2) identify control measures to roof safety that are being used in the Singapore construction industry; (3) evaluate these controls based on specific working on roof scenarios; and (4) investigate factors that influence the adoption of these solutions.

Literature Review

Causes and Risk Factors of Fall from Roof

Research efforts have been made to investigate causes and risk factors of fall from roof. For example, early in the 1990s, Johnson et al. (1998) found that noncompliance with fall protection regulation

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and lack of fall protection systems are the main causes of fall from roof. These two main causes can further be attributed to a number of factors, including unsafe behavior, design difficulties, lack of knowledge, and competitiveness of home building and roofing industries. In the 2000s, Kines (2002) examined risk factors for fatal versus serious injuries of FFR in the construction industry. The results suggested that fatigue is a contributing factor of fatal fall accidents, while serious fall incidents are linked with the use of passive personal fall protection equipment. Similarly, Huang and Hinze (2003) conducted a study which aims to identify the root causes of fall accidents by examining fall accident occurred from January 1990 to October 2001. The study suggested that root causes include a wide range of human errors, such as misjudgment of hazardous situations, safety devices removed or inoperative, equipment in use not appropriate for operation or process, etc. Hsiao and Simeonov (2010) conducted an extensive literature review of fall from roof and summarized environmental (e.g., visual and physical interactions), task-related (e.g., loading handling, fatigue, and complexity of task), and personal (e.g., individual differences, work-job experience, and training) factors to fall accidents. In addition, Bobick (2004) analyzed all fall accidents between 1992 and 2000 in the US and found that lack of positive safety attitude and supervisory support played important roles in fall accident causation processes. Sa et al. (2009) compared commercial and residential roofers with regard to behaviors, beliefs, working conditions, and attitudes toward the use of fall protection devices. Results indicated that residential roofers were more likely to fall than commercial roofers and that self-employed workers had a higher rate of injury than non-self-employed workers. The disparity was caused by a number of factors, like self-employed workers tend to work alone and longer and they are not enforced to use fall protection devices. Moore and Wagner (2014) studied 112 residential roofing fatalities reports and identified 14 contributing factors to roofing fatalities. Among these 14 factors, lost balance/slip/trip, lack of concentration, lack of training are the most common causes. An interesting finding by Kines (2002) is that the presence of fall protection systems may change workers' perceived level of risk and therefore they may adjust their behavior in response to the change. A list of causes and risk factors that were identified by previous studies is presented in Table 1.

Solutions to Fall from Roof

To prevent fall from roof accident and injuries, a range of control measures has been investigated and proposed. For example, researchers believed that enforcing roof safety regulations is critical to deter noncompliance on construction sites (Dong et al. 2013). Legal requirements for roof safety are an important part of the over-arching health and safety (H&S) legislative framework in many countries. For example, The Work at Height Regulations 2005, UK, require employers to ensure that (1) all WaH is properly planned; (2) those involved in WaH are competent; (3) the risk of FFH is assessed and appropriate work equipment is selected and used; (4) the risk of working on or near fragile surfaces is properly managed; and (5) the equipment used for WaH is properly inspected and maintained (The National Archives 2005). The Regulations proposed a hierarchy which defines three levels of FFR controls: (1) avoid work at height where they can, (2) use work equipment or other measures to prevent falls where work at height cannot be avoided, and (3) use work equipment or other measures to minimize the distance and consequences of a fall should one occur. The hierarchy is consistent with the general hazard control hierarchy which defines hazard control into five levels: elimination, substitution, engineering control, administrative control, and personal protective equipment (PPE). Similarly, OHSA (Occupational Health and Safety Administration), US, also requires employers to take specific precautions to protect employees working at height (OSHA 2015).

In order to deal with the unwavering high number of FFH cases in Singapore, the government has continuously developed measures with stringent enforcement, regulation and best practices implemented. The amendment the Workplace Safety and Health Act (Chapter 354A), Workplace Safety and Health (Work at Heights) Regulations 2014 came into force on 1 May 2014 (WSHC 2006). Under this act, the government commenced the implementation of the two enforcements: Fall Prevention Plan (FPP) and Permit to Work (PTW) for WaH. With the implementations, workers will be obliged to possess and understand the relevant skills in order to better comprehend, control and deal with WAH risks.

To support the construction industry and employers, a number of WaH standards and best practices were developed and published, such as British Standard BS 8560:2012 in the UK (BSI 2012), "Best practice guidelines for working on roofs" in New Zealand (MBIE 2012). The Ministry of Manpower, the Workplace Safety and Health Council and the National Work at Height Safety Taskforce jointly issued a report on Safety Analysis & Recommendation Report on Work at Height, which was substantiated by a study of 126 FFH cases (Ministry of Manpower 2009).

Dong et al. (2013) examined trends and patterns of FFR fatalities in the US construction industry between 1992 and 2009. The study found that 67% of fatalities occurred in small construction establishments (1–10 employees). In order to reduce FFR accidents, they recommended that fall protection equipment be properly developed and used. Due to the fact that FFR accidents occurred because of fall protection equipment failure, researchers examined the effectiveness of different fall protection equipment and tools. For example, Bobick et al. (2010) tested the effectiveness of guardrail systems to prevent falls through roof and floor holes. They recommended that proper materials and fasteners be used to construct guardrails. Goh and Wang (2015) evaluated eleven horizontal lifeline system (HLLS) designs in Singapore and found that

Table 1. Causes and risk factors of fall from roof

Common causes and risk factors	References
Noncompliance with fall protection regulation	Johnson et al. (1998)
Work situation (complexity of task); fatigue; personal fall protective equipment failure; work-job experience	Kines (2002) and Hsiao and Simeonov (2010)
Human error	Huang and Hinze (2003)
Poor safety attitude; lack of supervisory support	Bobick (2004)
Working alone;	Sa et al. (2009)
Loss of balance; lack of concentration; lack of training	Moore and Wagner (2014)
Poor engineering design	Grant and Hinze (2014)
Risk compensation	Kines (2002)

Table 2. Solutions and control measures to fall from roof

Solutions and control measures	References
Work at height regulations	Johnson et al. (1998) and Dong et al. (2013)
Financial penalties	Moore and Wagner (2014)
Roofing safety training	Huang and Hinze (2003), Dong et al. (2013), and Evanoff et al. (2016)
Active fall protection devices	Lan and Galy (2016), Goh and Wang (2015), and Goh and Love (2010)
Passive fall protection systems	Bobick et al. (2010)
Scaffold and/or work platform	Johnson et al. (1998)
Fall protection programs (e.g., fall protection plan and permit to work)	Dong et al. (2013)
Design for roofing safety (e.g., prefabrication)	Huang and Hinze (2003) and Behm (2011)
Campaign to roofing safety	Moore and Wagner (2014)
Information technologies and intelligent systems	Guo and Goh (2017), Goh and Guo (2018), Navon and Kolton (2006), and Zhang et al. (2015)

none of the eleven designs was adequately endorsed or calculated. Similarly, Lan and Galy (2016) evaluated a horizontal lifeline system (HLLS) used during installation of residential roofs. The results suggested that braced trusses could be used for fall protection. In order to facilitate the design of active fall protection system (AFPS), Guo and Goh (2017) developed an AFPS-ontology which captures the knowledge of the AFPS domain. Based on the ontology, they developed a web-based knowledge-based system which helps practitioners select a suitable AFPS (Goh and Guo 2018). FFR can be reduced by safer roof design. For example, Behm (2011) offered a number of design suggestions for roof access, fall protection, skylights, and structural integrity. Research attention was also paid on the health of roofers. For example, Wang et al. (2017) assessed risk factors for low back disorders among roofing workers. The study suggested that roof slopes, postures, facing directions, and working paces have strong impacts on low back disorders. A list of solutions and control measures to fall from roof that was proposed and/or developed in previous studies is presented in Table 2.

Adoption of Control Measures

To date, vert few studies were conducted to understand why workers and companies decide not to use existing solutions and control measures to fall from roof. Cattledge et al. (1996) studied 182 nonfatal construction falls in West Virginia and found that the reasons for not using fall protection devices include: (1) not needed; (2) not supplied; (3) too difficult to use while performing a job; (4) workers did not know what fall protection devices to use; and (5) work environment constraints. Moore and Wagner (2014) hold a view that involved cost is the major factor that hinders the adoption of the requisite safety measures. In addition, Huang and Hinze (2003) discussed that workers chose not to wear personal protective equipment because they think the PPE causes inconvenience and movement constraints or they just forget. Note that these efforts were limited to human and task-related factors. It is clear that why people choose not to adopt the existing solutions and control measures to fall from roof needs to investigated in greater detail by considering social, cultural, and organizational factors.

Methods and Materials

To reach the four research aims, a combination of interview and focus group discussion (FGD) was adopted as research methods. In specific, semi-structured interviews were conducted to (1) investigate causes of fall from roof; (2) identify existing roof safety solutions that are being used in the Singapore construction industry; (3) investigate factors that influence the adoption of these solutions; and (4) explore new solutions. Fall from roof is considered as a complex problem in this research. Qualitative semi-structured interview is more suitable research method than questionnaire as it enables researchers to gather more in-depth insights into the issue (Harris and Brown 2010). Based on the interviews, a number of critical and common work at roof scenarios were identified for the focus group discussion. The purpose of FGD is to make a prioritized selection of solutions to critical roofing scenarios through a ranked voting system and have an in-depth analysis of the possible solutions adoption factors to reduce the risk of FFR.

Interview

A total of eleven semi-structured interviews were conducted with thirteen experienced practitioners in the Singapore construction industry. Purposive sampling was adopted to select interviewees. Purposive sample is a non-probability sample that is selected based on characteristics of a population and the objective of the study using researchers' judgement and knowledge (Tongco 2007). The researchers understood that fall from roof is a complex issue and therefore it is important to interview with as many professionals and organizational levels as possible in order to construct a relatively comprehensive view of the issue from different perspectives. Thus, thirteen participants at different organizational levels and positions (e.g., contractors, architects, roofing specialists, authorities, facility managers, and safety control/equipment suppliers) were selected based on the recommendations by members of Institute of Engineers Singapore (IES) and the authors' contacts. Such a diversity is necessary, as it is important to capture opinions from different perspectives. Another selection criterion is that all interviewees should have a minimum of four years of working experience in the Singapore construction industry and extensive knowledge on site safety issues. The profiles of the interviewees are presented in Table 3.

The interview questions were focused on four main topics: (1) causes of fall from roof; (2) current solutions; (3) adoption issues; and (4) new solutions and challenges. All interviews were recorded with permission by the interviewees. A comprehensive transcription of interviews was produced with the aid of the audio recording. The interview data collected were transcribed and analyzed using NVivo (2016). Firstly, all responses were grouped to each question and topic. This helped the researchers to find and catalogue themes (e.g., adoption issues). This also enabled to make comparisons between participants by identifying conflicts and consistencies. Secondly, efforts were made to connect themes

J. Constr. Eng. Manage., 2019, 145(5): 04019027

Table 3. Profile of interviewees

No.	Industry discipline	Position	Years of experience
1	Authority/regulator	Principal Specialist	20
2	Main contractor	Senior Project Director	20
3	Main contractor	Head of Environmental Health and Safety Department	10
4	Main contractor	Safety Manager, Workplace Safety & Health Officer	18
5	Roof supplier	Safety Professionals	15
6	Roof contractor	Workplace Safety and Health Officer	14
7	Safety control supplier	Sales Manager	8
8	Safety control supplier	General Manager	20
9	Safety control supplier	Business Development Manager	5
10	Safety control supplier	Senior Marketing Manager	8
11	Safety control supplier	Director	20
12	Scaffold supplier	Director	18
13	Facility manager/owner	Estate Maintenance Manager	4

Table 4. Participants of the 1st FGD

Participant	Position	Years of experience
1	Principal Specialist	20
2	Senior Investigation Officer	20
3	Director of a scaffold company	18
4	Safety Manager of a main contractor	18
5	Safety Professional of a roofing company	15
6	Estate Maintenance Manager	4
7	Estate Maintenance Manager	15
8	Professional Engineer	18

Table 5. Participants of the 2nd focus group discussion

Participant	Position	Years of experience
1	Principal Construction Specialist	20
2	Senior Investigation Officer	20
3	Safety Manager of a main contractor	18
4	Safety Professional of a roofing company	15
5	Professional Engineer	18
6	Contractor	8
7	Owner	10
8	General manager	15

in order to better understand the complexity of fall from roof in the Singapore construction industry.

Focus Group Discussions

After the interviews and data analysis, two focus group discussion were conducted to discuss fall protection equipment and solutions for six critical and common roofing scenarios identified during the interviews. Focus groups are a form of group discussion that capitalizes on communication and interactions between participants (Stewart et al. 2007). It is usually led by a facilitator who is tasked to keep the discussion on track and encourage constructive contributions from the participants (Stewart et al. 2007).

Ten practitioners from the Singapore construction industry were invited to participate in the first FGD. Eight accepted the invitation and participated (Table 4). The selection of participants was made through purposive sampling (Flick 2009), which is similar to the previous method. Out of eight participants, six were chosen from the list of interviewed individuals while the other two participants were invited through the Institution of Engineers, Singapore (IES). Detailed work scenarios representative of the situation in the industry were presented prior to the FGDs to enable a more in-depth discussion on the solutions. At the same time, variations to the scenarios were discussed to assure that the findings can be generalized. This approach is useful in encouraging discussion and providing a context for assessing effectiveness of proposed solution. The topics of the first FGD were focused on two critical scenarios of activities on existing (old) roofs: (1) general maintenance tasks on existing roof; and (2) re-roofing and roof replacement.

The second FGD focused on new metal roof construction. Eight participants were selected and invited though members of the Institute of Engineers Singapore (IES) and the authors' contacts (Table 5). The second FGD was focused on four critical scenarios (activities) of new metal roof construction: (1) edge protection; (2) installation of metal brackets; (3) installation of purlins; and (4) installation of metal roof.

In both FGD, Borda count was adopted as a method to rank solutions to the critical roof-work scenarios. Borda count is a voting system for collective decision making (García-Lapresta and Martínez-Panero 2002). Borda's method takes into account all these preferences, allocating a value to each, and establishes winners by a simple tallying of the total value each solution acquires (Fraenkel and Grofman 2014; Reilly 2002). The method allows participants to rank the proposed solutions for each scenario in ascending order. For example, there is a total of four proposed solutions for a scenario; participants are allowed to give a ranking from first to fourth; a first rank is the most suitable solution and the subsequent ranks being the less effective solutions. Each ranking is given a weighted score; the scores allotted to each solution vary with the number of solutions. For example, there is a total of four proposed solutions for one scenario; a first rank will be given the score of four, the highest score while the last ranked solution of fourth will be given the lowest score of one. The total score for each solution will be computed after each discussion for each scenario. The solution with the highest score will hence be identified as the most effective, best-fit solution for the scenario.

The main benefit of choosing Borda's method is the simplicity of calculation to identify the best solution (Fraenkel and Grofman 2014; Reilly 2002). This benefit is significant because of the limited duration of FGD which gives no room for complicated and time-consuming calculations. Similar to the interview, the focus group sessions were voice recorded with the permission of the participants. The audio recordings were then transcribed and analyzed with the aid of NVivo 11 using the same methods and processes that were used to analyze the interview data.

Results

Causes of FFR

A number of major causes of FFR at different hierarchical levels were identified during the interviews. At the worker level, main causes include: (1) lack of hazard information; (2) lack of safety attitude and awareness; (3) lack of WaH knowledge; (4) lack of appropriate devices and tools; and (5) violation of the code of practice.

All interviewees pointed out that workers' safety knowledge and awareness is a major contributing factor to FFR. The Singapore construction industry consists of a large number of foreign labors with low levels of education. As Interviewee 3 pointed out:

> "The second (issue) is the literacy level. If you notice, if we talk about PE design, drawing all these (sic), these are engineering terms, and engineering drawing, these are technical things. Even the fall from height computation, these are technical things. In terms of numeracy, literacy, they are not there."

Accompanied by a low level of safety knowledge is poor safety awareness. More often than not, workers go up to roof without asking for hazard information and protection devices from supervisors and managers.

Lack of supervision is the main contributing factor at the supervisor level. As Interviewee 5 pointed out:

> "It took us for a while to figure out that actually the full time supervision is critical. Sometimes I was told that supervision is important and everyone knows that. But sometimes when it gets to the ground, some supervisors don't go up on the roof and just told that their workers to take their PPE to protect themselves."

At the organizational level, lack of safety commitment and lack of capability are two main causes of FFR. Key findings of causes of FFR are presented as follows. In some cases, FFR accident occurred because of lack of supervision. Supervisors tend to pass fall protection equipment (e.g., harness and lifelines) to workers with incomplete safety knowledge and ask them to protect themselves. The importance of full-time supervision was emphasized by a number of interviewees. As Interviewee 6 stated that:

> "So, again human nature, if there is somebody checking the workers, workers will not do shortcuts. Workers will not do funny things. And that is the role of the supervisors. So if the supervisor is good, competent, these things will unlikely happen (sic). For example, this thing will not happen, if the supervisor is competent. At first they will not allow them to do that, this will not be allowed."

This was echoed by Interviewee 4, who pointed out that they require their worksite to be supervised at all times.

> "..., whenever roofing (sic) there must be a supervisor to supervise at all times."

The Singapore construction industry is largely composed of small subcontractors. They have demonstrated limited capability to understand and implement the Singapore WaH code of practice. As Interviewee 10 stated that:

> "I am not sure whether the organization (small companies) even understand the code of practice on working at height."

Contractors' safety motivation is another important problem. In contrast to some companies which have a positive safety culture, some have shown indifference toward workers' lives. According to Interviewee 4, the power imbalance between employers and foreign workers (Teo and Goh 2016) contributes to foreign workers working in unsafe conditions. In addition, contractors' commitment to safety has often been undermined by production pressure, cost issues, the local lowest-price tendering system.

As suggested by most interviewees, key stakeholders' attitude toward roof safety is generally and alarmingly poor. For example, owners show resistance adopting certain solutions due to cost, productivity and aesthetic issues. Interviewee 4 mentioned this problem during the interview:

> "As for the owner, they feel that they contract out the job to the roofing contractor, so the contractor should take care of their own safety."

Another common source of problem is the contractors' middle management. For example, Interviewee 8 pointed out that inexperienced purchasing managers, who have little knowledge on roof safety, are often responsible for purchasing of equipment and tools for roof safety. In addition, Interviewee 3 indicated that the responsibility for training workers to use roof safety equipment and tools is often not clearly defined on the ground.

Existing FFR Control Measures

Interviewees provided a number of existing control measures that are commonly being used in the Singapore construction industry to prevent FFR. A 5-level hierarchy used by the Safe Work Australia (2016) was adopted to categorize FFR control measures. Level 1 controls aim to eliminate the risk of a fall by either carrying out tasks on the ground or platforms (e.g., flat roof) with edge protection (e.g., parapet). Level 2 controls represent fall prevention devices and equipment, such as temporary work platforms (e.g., scaffold, elevating work platforms, step platforms, mast climbing work platforms, and ladders), guardrails, and safety mesh. Level 3 controls include any work positioning systems that can restrain workers within safe areas. Level 4 controls are used to arrest a fall when it is not reasonably practicable to prevent a fall. For examples, catch platforms, and active fall arrest systems are common measures to arrest a fall. Safety net should be used when it is not practicable to provide scaffolds or temporary guard railing. Level 5 captures all administrative controls such as safety training (Table 6).

Solutions to Critical Roof Work Scenarios

To facilitate the FGD, six critical roof work scenarios were identified during the interviews, including: (1) general maintenance tasks on existing roof; (2) re-roofing and roof replacement; (3) edge protection; (4) installation of metal brackets; (5) installation of purlins; and (6) installation of metal roof. Singapore has a large number of old roofs which require regular maintenance and even replacement. As such, Scenarios 1 and 2 represent very common roofing practices in the Singapore construction industry. Scenarios 3, 4, 5, and 6 represent critical WaH activities (stages) of new roof construction.

Scenario 1: General Maintenance Tasks on Existing Roof

The first scenario focuses on general maintenance tasks, inclusive of roof maintenance and other maintenance works that are carried out on existing roofs. Roof maintenance refers to the general task of fixing common roof problems such as fixing a leaking spot or

J. Constr. Eng. Manage., 2019, 145(5): 04019027

Table 6. FFR control category

Control category	Control mechanism	Specific solutions
Elimination	"Design out" or minimize fall hazards	Prefabricated prefinished volumetric construction (PPVC)
		Cross Laminated Timber (CLT)
		Early placement of permanent anchors
		Parapet
		Permanent barricade
Fall prevention systems	Prevent a fall from happening	Guardrail systems
		Skylight cover
		Skylight guardrail
		Safety mesh
		Scaffold
		Walkway system
		Cage ladder
		Mobile elevating work platform (MEWP)
		Mast climbing platform (MCP)
Work positioning systems	Enable a worker to be positioned and safely supported at a work location to carry out a task	Travel restraint systems
		Industrial rope access systems
Fall arrest systems	Arrest workers once a fall happens	Vertical lifeline systems
		Horizontal lifeline systems (HLL)
		Self-retracting lifeline
		Safety net
		Temporary anchor systems
Administrative controls	Alter the way the work is done	Warning line system
		WaH training
		Fall prevention plan
		Daily inspection checklist

cleaning the roof parapet. The other maintenance works include the maintenance of cooling tower or fixing of electricity wirings that are located on the roof.

The scenario is general on purpose and a list of variables and parameters applicable to the scenario is described to encourage a holistic approach in conceptualizing the well-suited solution. These variables and parameters include:

1. Roof slope—pitch or flat
2. Availability of anchor—with or without
3. Presence of skylight—with or without
4. Condition of skylight—difficulty-to-identify (invisible) or visible
5. Presence of parapet—with or without
6. Height/elevation—2–5 story height

From the focus group discussion, the participants suggested five possible solutions to the scenario, including: (1) fall arrest system (harness, lanyard and anchors); (2) mobile elevating work platform (MEWP); (3) horizontal lifeline (HLL) and catwalk panel; (4) scaffold and mast climbing platform (MCP); and (5) and man cage. Each solution was discussed and then voting was carried out to rank the solutions. As presented in Table 7, fall arrest system (FAS) was ranked as the most suitable solution to the Scenario 1, followed by boom/scissor lift and HLL and catwalk panel. Despite both categorized as a PPE control, fall arrest system is preferred as compared to horizontal lifeline. The reason is the concern on misusing the horizontal lifeline as stated by the Participant 5 below:

Table 7. Ranking of solutions for Scenario 1

Solutions	Score	Rank
FAS (lanyard directly connected to anchor)	33	1
Boom/scissor lift	31	2
HLL + catwalk	26	3
Scaffold + MCP	22	4
Man cage	8	5

> "People misused it. Too many people hook on… When multiple people hook on, the equation is different already."

Scenario 2: Re-Roofing and Roof Replacement

The second scenario focuses on the re-roofing and roof replacement. A common example is the major replacement of all roof tiles. These work are often carried out on old existing buildings through upgrading project in Singapore. Substantial maintenance work such as re-roofing involves the replacement of roof components on the existing building, without affecting any structural elements of the building. Similar to the first sub-scenario, the possible variances in roof replacement work are specified to facilitate the brainstorming of the possible solutions. The variances are listed down as per below

1. Roof slope—pitch or flat
2. Roof material—fragile or not fragile
3. Availability of anchor—with or without
4. Presence of parapet—with or without
5. Height/elevation—2,5 and 10-story high

For further specification of the scenario, the process of re-roofing is divided into two methods. Firstly, the process of removing and replacing the tiles pieces by pieces with operation still ongoing in the building. The second variance depicts the situation where the entire roof structure is stripped off. The floor below the roof is vacated, providing a working space below the roof. The participants suggested seven possible solutions to the scenario, including fall arrest system, MEWP, barricade, airbag, hanging scaffold, cantilever scaffold for edges, and rope access system.

For the second scenario, the result of solutions ranking is presented in Table 8 below. Results indicated that FAS was again voted as the most effective solution for the scenario. A question was raised on the rationale for choosing Solution 1: fall arrest system over Solution 7: rope access system which was deemed to be similar in nature. The justification from the participants is mainly based on the different level of competency of workers on deploying fall

J. Constr. Eng. Manage., 2019, 145(5): 04019027

Table 8. Ranking of solutions for Scenario 2

Solutions	Score	Rank
FAS	52	1
Cantilever scaffold	41	2
Working platform with scaffold	37	3
Boom/scissor lift	36	4
rope access system	31	5
Airbag	13	6
Barricade	3	7

Table 9. Preferred solutions for edge protection

Solutions	Score	Rank
Permanent handrails (designed in)	51	1
Fall arrest net with edge protection	48	2
Scaffold	32	3
Counter weight guardrail	32	4
Clamp on guardrails	30	5
Catch net	23	6
Warning line system	7	7

Table 10. Preferred solutions for installation of metal brackets

Solutions	Score	Rank
Cast in brackets	35	1
Install before dismantling of formwork	28	2
Use prefabricated steel structure	26	3
Install using MEWP	22	4

arrest system and rope access system. In general, rope access workers are highly trained and competent, but the general workers working in Singapore are usually only familiar with simple fall arrest system (harness, lanyard and anchor). Thus, Solution 1: fall arrest system was deemed to be the most practicable solution in this scenario.

Scenario 3: Edge Protection of New Roof Construction

The participants suggested seven possible control measures for edge protection on roofs (Table 9). The most preferred solution was to have permanent handrails designed in, as it was deemed to be the most cost-effective. In cases where aesthetics was of concern and in the case study of a typical metal roof, having a fall arrest net that comes with edge protection as well was ranked second, followed by the widely used scaffold.

Scenario 4: Installation of Metal Brackets

Installing metal brackets is an essential activity of new metal roof construction. In general, metal brackets are installed to support purlins. This activity involves high risk of fall from height. The participants proposed four possible solutions to this scenario (Table 10). The most preferred solution is to have cast in brackets during concrete casting of the reinforced concrete beams. The main advantage is that the method eliminates the need for installing brackets after the reinforced concrete beams are completed. However, there are limitations. During concrete casting, workers would have to insert the vibrator into the viscous cement and this movement is likely to cause the brackets to be dislodged or displaced. The second most preferred solution was to install these brackets before the dismantling of formwork. However, this has frequently been overlooked by main contractors and ended up with no bracket being installed. They have to install brackets after the formwork has been dismantled using boom lift or scissor lift. Despite that using MEWP is a common industrial practice, it was actually the least preferred method, as it was not deemed to be cost-effective and subject to site constraints (e.g., slope and strength of ground). When site conditions are not satisfactory, using MEWP only causes more safety risks.

Table 11. Preferred solutions for installation of purlins

Solutions	Score	Rank
Full working platform	38	1
Boom lift or scissor lift	30	2
Spread purlins and tie together	19	3
Safety net in the form of fall arrest net	17	4
Safety net in the form of a net platform	13	5

Table 12. Preferred solutions for installation of metal roof

Solutions	Score	Rank
Safety mesh	48	1
Fall arrest net with edge protection	36	2
Fall arrest—typical lanyard system	26	3
Travel restraint	26	4
Self-retracting lanyard	22	5
Airbag	9	6

Scenario 5: Installation of Purlins

Another common activity of new roof construction is to install purlins. The participants identified five possible solutions to reduce the risks of falling from height when installing the purlins (Table 11). Purlins are usually installed after brackets are completed. The most preferred solution was to have a full working platform to install purlins. This would be the ideal case if there is no cost constraint. The second most preferred solution was to use boom lift or scissor lift, which is a common industrial practice. A unique method of rigging several purlins together for lifting and installation concurrently was shared during the FGD. However, craneage constraints (e.g., slope of ground and space for crane operation) would deem to make this method impractical. Safety nets, be it fall arrest net or net as a working platform, are the least preferred solutions. When using safety net to catch a fall, fall distance is a critical factor that must be taken into account. Professional Engineers (PE) must be involved to calculate the strength of anchor and dynamic force of a fall. This would cause more cost. Using safety net as a platform could be more flexible than scaffold, as it can be fast (un)installed to server changing work areas. However, net platform is less common in the Singapore construction industry, as most practitioners are not familiar with it.

Scenario 6: Installation of Metal Roof

Six possible solutions were proposed to reduce the risk of falling from height when installing the metal roof and the various layer or components of it (Table 12). The most preferred solution was to use safety mesh. It was deemed to be cheap and practical. A fall arrest net with edge protection was also discussed during the FGD. It was the second most preferred solution, as it provides two hazard control mechanisms simultaneously: prevent a fall and arrest a fall. The typical fall arrest system (harness, lanyard and anchor), which is commonly used in the industry, was the next preferred, followed by travel restraint and the self-retracting lanyard. The major drawback of travel restraint system is that it significantly restrains workers' movement. Inflating an airbag was the least preferred method as the method is time consuming and may hinder other activities.

Solution Adoption Factors

As aforementioned, a number of fall protection solutions exist in the industry and market but some contractors are not willing to implement them during roof work. This subsection presents interviewees' opinions of what factors affect the selection and implementation of existing solutions to FFR. Four major factors were identified through interviews, including: (1) cost; (2) time pressure; (3) power imbalance; and (4) on-site constraints.

Cost

All interviewees believed that cost is a major factor that hinders the adoption of solutions to FFR. It consists of money spent on purchasing, installing, and maintaining tools and equipment, and training workers. Interviewee 11, a director of a safety equipment supplier, stated:

> "... we do have companies who come to us and we propose a solution and they were not aware that the solution is going to cost so much. They were wanting something that is less than a thousand dollars."

As expected, compared to established and large contractors, small-sized ones are more reluctant to adopt expensive solutions to FFR.

Interviewee 11 explained:

> "Smaller contractors usually ... "reengineer" on their own, many of them tried to do that ... Yeah, so the experience [sic] we install some system on the certain sites and after that you can see them trying to duplicate the same systems on their own."

As a result, these smaller companies tend to buy tools and devices from small hardware shops who typically, as Interviewee 8 stated, *"(do) not have very good knowledge of working at height"*. Therefore, the tools these smaller companies buy may not be suitable for their WaH.

In addition, the maintenance of solutions is costly. Extra resources are needed to clean, inspect, and store tools and equipment (e.g., safety net). Some interviewees believe that the extra cost incurred from maintaining the solutions often deters the adoption of the solutions. Interviewee 6 highlighted this maintenance cost issue, especially in the private sector:

> "... the private sector, the private owner, they are kind of reluctant to install because when you have the permanent lifeline system, you have additional costs and also maintenance of the lifeline. You know every years you need to actually have regular check on the lifeline, and all these are costs."

Some interviewees from contractors pointed out that the cost issue was in part caused by current tendering systems. With low tendering price, contractors may have no budget to buy solutions from the market. As stated by Interviewee 1:

> "Yes, they will look for the lowest price. And they don't bother, to them, it's like, safety is your (contractor) problem. How you do the job? I don't care. How they manage the workers, I don't care. Bear in mind, in Singapore, we have this tendering system that is looking at the lowest price in the entire Singapore."

This was echoed by Interviewee 12 who pointed out that:

> "The industry players seem to fighting on their pricing without taking consideration of any additional safety provision."

Time Pressure

Implementing a solution to FFR often requires relevant training and installation, which is time-consuming. For example, adopting safety netting as a fall protection system requires extensive training and intense preparation to calculate and set up. Due to time pressure in construction projects (Guo et al. 2016), practitioners prefer passive systems solutions which pose less time requirements for training and attention. In the battle between time and safety, most people are not willing to sacrifice the latter.

As Interviewee 12 stated:

> "These workers work based on hourly rate, the faster they complete the job, the faster they earn. They might feel, by installing the safety device, it would cause half of the time needed for the roofing work."

Power Imbalance

Power imbalance is another key barrier to the selection and implementation of appropriate solutions to FFR. Power imbalance captures the difference in the power of different actors. According to the interviews, it was found that power imbalance existed between (1) employers and workers and (2) owners and contractors. In the Singapore construction industry, foreign workers' dependence on their employer is high, but the employer's dependence on workers is generally low. Due to the power imbalance, it is difficult for workers to be involved in safety assessment and planning. Because of the fear of losing job, they often have no option but to perform tasks as they are told without asking for necessary hazard information and fall protection equipment.

According to Interviewee 13:

> "Workers were really very innocent. Whatever their supervisor or whatever the manager tell them to do, they will just follow. Their knowledge of the risk involves is very low. You tell them to do anything, they will just do."

This was echoed by Interviewee 9 who pointed out that:

> "There is a dilemma between employer and employee. Employees do not know the risk, they will be like, they ask me to do and then I'll do it. Employer may be aware (the risk) but there is a cost constraint."

Often in times, the consequence of the power imbalance is that the side with less power sacrifices their own interest in order to satisfy the other party. As a result, workers have to rely on their attention and limited safety knowledge to protect themselves, which is inadequate in many scenarios.

Power imbalance also existed between contractors and owners. Roofers have to use temporary anchors because owners refuse to install the barricade on existing roofs, while the roofers may not have competency to identify appropriate anchor or may not be willing to set up a temporary anchor for a five-minute patching work.

> "Sometimes, the inspector needs to inspect at the edge of the building for weed, to remove these weeds. Then the issue is, can you resolve it with engineering? No way. Unless you install the barricade. The workers, is beyond their control you see, they have no say. They can't tell the owner, "You install the barricade then I come and do the service". The owner will

say, “No. My roof has always been like that for many years. You just go and solve my problem.”

On-Site Constraints

There are a number of on-site constraints that make the implementation of solutions difficult and even impossible. These constraints include, but are not limited to, slope of ground, damage to structure, space constraint and reach constraint. For example, installation of a FFR solution may damage existing roof structure. In addition, installing permanent barricade systems on the roof may negatively affect the aesthetic of building. Interviewee 8 provided an example of installing the barricade system:

> “For example, certain roof is finished with waterproofing, the owner doesn’t allow you to drill holes and install barricades.”

Space constraints refer to the lack of space for the safety equipment to enter and be placed on site. In some situation, engineering solutions are not applicable and personal protection equipment must be chosen. As Interviewee 1 pointed out:

> “So we need to accept certain limitation, especially old buildings. These are the older problem, those kind of buildings, there is no way we can resolve with engineering control or resolve by design. Unless you tear it down. So at this moment, for these old buildings, we have to live with the PPE and lifeline solutions. You need to consider both.”

Meanwhile, reach constraint refers to the inability of the equipment to access all the areas of work. One example is the deployment of boom lift. To allow the boom lift to make an entrance and standby on-site, it needs a considerably wide space. Also, the working platform can only reach specific angles of roof, depending on the location of the boom lift.

Another important issue is that certain solutions may hinder other tasks and activities. Interviewee 3 explained this issue using an example of using a scaffold in the middle of a building. He stated:

> “While I do my middle platform scaffold . . . many situations the roof haven’t come in, they have this middle part but they need to do something to the floor, so they have to take out everything . . . but when this roof come in and there is no support in the middle and the people still want to do the tiling on the floor . . . So who got the top priority?”

When the implementation of a solution affects other work, it can lead to the delay and thus discourage managers from adopting the solution.

Discussion

This paper represents an effort to provide insights into why workers fall from roof and companies do not implement fall protection solutions that already exist in the industry and market. In general, roof work in the Singapore construction industry is very hazardous. Many unsafe roofing practices exist in the industry. Unqualified roof workers work without adequate supervision and the necessary PPE. Owners/developers have limited ownership of roof safety and small roof contractors do not adopt right safety tools and equipment. The results from the interviews suggested that FFR accidents and injuries are not caused by isolated factors and stakeholders, but a complex web of factors at different hierarchical levels.

As shown in Fig. 1, two fundamental factors govern the behavior of workers, safety attitude/awareness and WaH knowledge. These two factors are controlled by supervision at the supervisor level, safety commitment of their employers, and WaH training as required by the government. As mentioned before, there may be power imbalance between workers and their employers. It happens when workers have a high level of dependence on their employers for their livelihood and safety is not their priority.

For contractors, the commitment to adopt and implement appropriate fall protection tools and devices is affected by cost, time pressure, and on-site constraints. The power imbalance between owner and contractor is also another possible issue. Power is not necessarily permanently owned by certain individuals (e.g., employers). It is a product of social relationships in a certain social context (Emerson 1962). This implies that it would be difficult to fundamentally change the power relations in a relatively stable social context. Thus it becomes critical to address the dominant actors by improving their safety awareness, commitment to safety, and accountability.

One common dilemma facing roof contractors is the conflict between low profit margin and high cost involved in buying and installing safety tools and equipment. The conflict becomes even more painful in current context where tendering systems are dominated by price. When developer/owners stay out of investment on roof safety, roof contractors can do nothing more than implementing relatively cheap, while not reliable, administrative controls.

As suggested in FGD, different solutions can be applied to a certain specific roof work scenario. However, some solutions were deemed more suitable than others. According to participants, cost-effectiveness, workers competency, and site constraints are the most critical factors that differentiate solutions. In general, projects tend to choose solutions that are simple-to-use, reusable, and cost-effective. For example, FAS is more suitable than rope access system because the former requires less competency to install and use. MEWP can be applied to most of roofing scenarios, but it is subject to site constraints, such as slope of ground and space. Participants proposed a number of “design-for-safety” solutions that can potentially improve roof safety, such as off-site prefabrication and prefabricated prefinished volumetric construction (PPVC). The methods avoid much of work at height. However, the solutions are subject to transportation and space issues. It is not cost-efficient to apply it to small projects because all costs involved are high. In addition, projects are less likely to adopt solutions that can cause barriers to other site activities.

Considering multiple factors that come into play, preventing falls is challenging and it seems that there is no quick fix to the problem. To tackle the complex problem in Singapore, establishing a roof association (RA) or union may be a good initiative. The suggestion of developing a roofing association was raised up during the focus group discussion. In fact, roofing associations were established in other countries like the US, UK, Australia, and New Zealand and these associations are playing important roles in representing the interests of and speaking for their members. A united voice from roof contractors, manufacturers, distributors, and specialist would also be beneficial to improve roof safety if the possible roofing association addresses the following issues: (1) design working-on-roof best practices, (2) improve tendering process, and (3) develop and manage a licensing roofing worker program. Previous research has proved that union workers are more likely than non-union workers to have a higher level of safety awareness, control, and motivation to participate in safety practices (Dedobbeleer et al. 1990; Gillen et al. 2002).

Workplace Safety and Health Council, Singapore developed and published ‘Workplace Safety and Health Guidelines —Working safely on roofs’ in 2013. With convening power to bring together roof contractors of all sizes in the industry, a roofing association

J. Constr. Eng. Manage., 2019, 145(5): 04019027

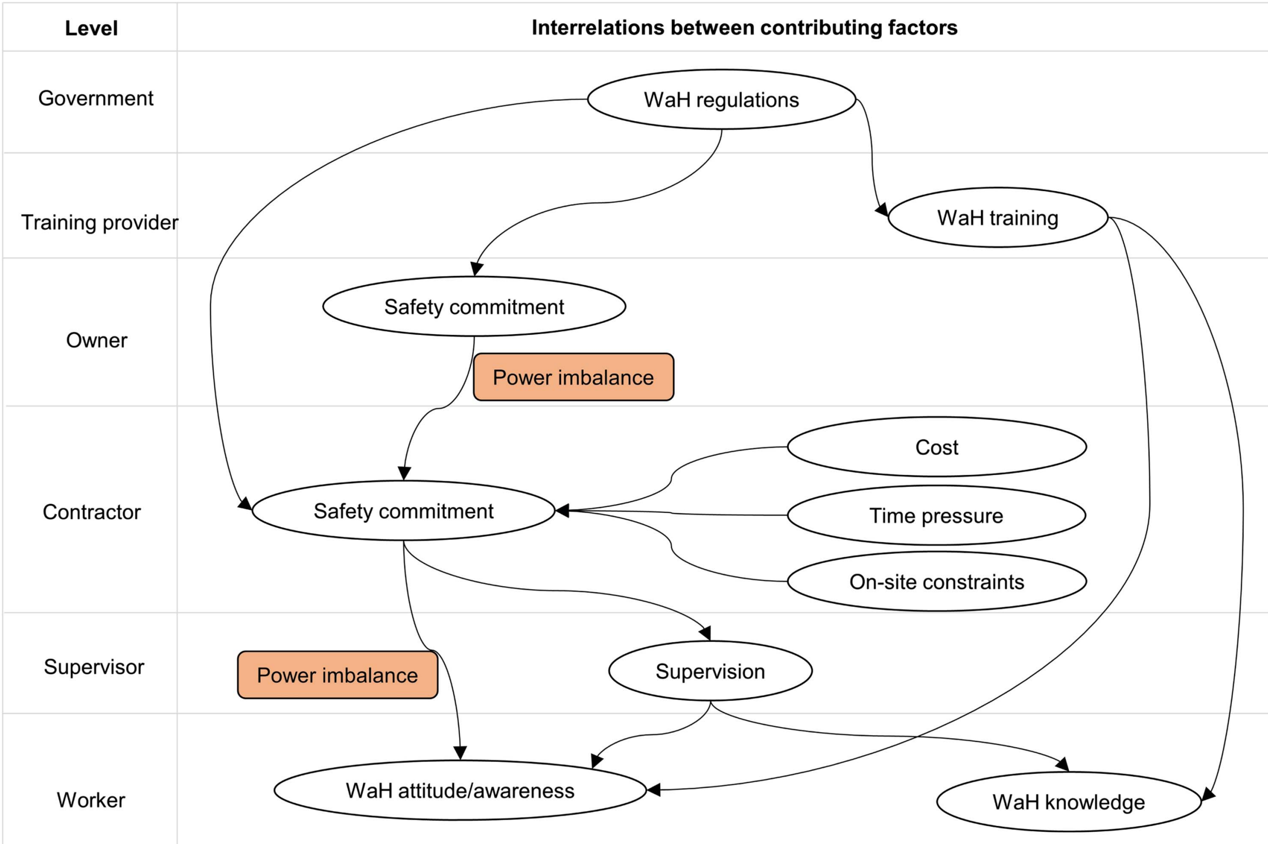

Fig. 1. Interrelations between contributing factors at different hierarchical levels.

can, in association with relevant government agencies, update current guidelines of working safely on roof. Emphasis can be placed on how to help roof contractors select right solutions to specific scenarios according to roof work, roof type, material, slope, etc.

RA should be well equipped to offer information, advice, and guidance on roof work. Roof contractors vary in terms of size and capacity. Small businesses often have problems to obtain useful information about new products, technology, and safety equipment from the market. RA should provide its members, especially small ones, with latest news, information, design for safety ideas, and technology about roofing industry. By working with roof associations in other nations, RA can promote innovation and the transfer of technology. This can help members improve competitiveness and safety performance as well.

RA can have significant influence on tendering process. As a trusted voice of roof industry, RA can engage with policymakers and developers/owners to advance tendering policy and process issues, making roof safety management easier for roof contractors. For example, developers/owners may consider setting a separate budget for safety and thus easing the financial burden of roof contractors.

Roofing is a specialist trade. But it is common that unqualified roof contractors win roof projects. RA should develop and manage a licensed roofing worker program to elevate roofing workers' skills, knowledge, and professionalism. Different license could be targeted to different roofing contractors like residential, commercial, and industrial. RA can encourage developers/owners to integrate the licensing into tendering process so as to make sure only qualified and licensed roof workers can work on roof.

The results also suggest that both roof contractors' and workers' knowledge of roof safety are still low. Safety education and training is still essential. A recommendation from interviews and focus group discussions is that specific work-on-roof training should be designed and provided to all roofers. Interviews and focus group discussion participants suggested that current WaH training is relatively general and ambiguous for roofers. This is confirmed by the participants' comments on the current WaH courses below.

> "The training part also, if you look at work at height training courses, one of the courses, is talking about this installation, only talk about usage."

> "Yeah, what we do . . . sometimes we are very ambitious, we want to train everybody. But the thing is . . . we train everybody but very a little bit only, then the real one come in. all just a little bit trained, so if you are talking about roof only, then maybe we can just focus train this group of people doing roofs."

Hence, the recommendation to create and drive for a specific work-on-roof training will allow more specialized content for roofing work in identifying hazards and adopting suitable safety controls. The medium of training has to emphasized more on practical session than theory session. This will encourage a hands-on learning process with a more applicable and fitting content to roofing work. RA can bring roof-oriented education and training to members. Different training programs can cover different topics, such as construction method, technology, and health and safety.

In addition, project planning and coordination between different trades is important. For example, roof contractors and formwork subcontractors are likely to work at the same time on site. The roof contractor could utilize the formwork as a platform to construct the roof. However, due to poor planning and coordination, formwork subcontractors tend to ignore the need and would like to disassemble the formwork so that it can be used on other sites. As a result, the roof contractor would have to choose other less cost-effective solutions.

Conclusions

This paper investigates FFR with respect to causes of fall, existing solutions, solutions to critical roof work scenarios, and factors that influence solution adoption. Results indicated that FFR accidents and injuries were caused by a combination of individual and organizational factors. In specific, individual factors include: (1) lack of hazard information; (2) lack of safety attitude and awareness; (2) lack of WaH knowledge; (3) lack of appropriate devices and tools; and (4) violation of code of practice, while at the organizational level, lack of supervision, lack of safety commitment and lack of capability are key contributing factors. Note that these contributing factors were not derived from accident investigation reports, but represent perceptions of interviewees based on their rich experience in the industry.

According to the interviewees, a number of FFR controls are being used in the Singapore construction industry, ranging from engineering design, fall restraint, fall arrest, roof access, and administrative controls. Efforts were made to identify the most appropriate control measures for six specific roof scenarios. According to the participants of the focus group, fall arrest system was voted as the most effective solution to Scenarios 1 (i.e., general maintenance tasks on existing roofs) and 2 (i.e., re-roofing and roof replacement). Not surprisingly, permanent handrails were considered the most suitable solution to edge protection. Cast in brackets was voted as the most appropriate solution for installation of metal brackets. In terms of roof construction, installing a full working platform was believed as the most preferred solution to purlin installation, while safety mesh is a preferred solution for installation of the metal roof.

Despite these existing solutions, it was found that some contractors are reluctant to implement appropriate solutions in their roof work. Contractors' and owners' decision making was influenced by cost, time pressure, and on-site constraints. The power imbalance between (1) workers and their employees and (2) owners and contractors is another important factor that comes into play in the particular context in Singapore.

Based on these findings, it was suggested that establishing a roof association would help reduce FFR accidents and injuries by addressing the following issues: (1) design working-on-roof best practices; (2) improve tendering process; and (3) develop and manage a licensing roofing worker program. As current WaH safety training has been too general to equip workers with specific roof safety knowledge, it was suggested that work-on-roof training be developed in the construction industry.

This paper embarked on a present urgent topic of fall from heights with a specific focus on fall from roof. Even though many studies have been done on the general topic of falling from heights, there appears to be a lack of a study which comprehensively addresses causes of FFR, existing solutions, evaluation of solutions, and factors that affect solution adoption. Although the causes of FFR were not derived from accident reports, they represent the perceptions of people who have had rich experience and knowledge in accident investigation, roof safety management, and fall protection solutions. The evaluation of solutions to critical working-on-roof scenarios complements current WaH best practices and guidelines. More importantly, the factors that influence the adoption of fall protection solution capture key deep-rooted causes of FFR accidents. These factors are beyond immediate human errors but closely related to the unique construction context. They draw a richer picture of roof safety in the construction industry. They were seldom captured in accident investigation reports and therefore they offer insights into FFR accident prevention.

This paper is not without limitations. The major limitation is that this study was conducted in Singapore. The results and recommendations should be applied to other contexts and countries with caution. Another limitation is that the scenarios identified and discussed in this paper are by no means comprehensive. Other common scenarios can, and should, be identified by future studies. Last but not the least, this study did not collect any data directly from workers. Future research should complement this by obtaining workers' insights into fall from roof.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the *Journal*'s data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

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