DESIGN-FOR-SAFETY ANALYSIS SUPPORT SYSTEM FOR BUILDING DESIGNERS

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ABSTRACT: *Accident prevention and control in construction is a continuing challenge. The construction industry has one of the worst workplace health and safety records globally. There is considerable evidence that decisions made by designers early in the development process have significant implications for the safety of workers on construction sites. Recognizing the important contributions which good design can make in improving safety performance, many governments around the world have mandated Design-for-Safety (DfS) in their workplace health and safety legislations. Designers in many countries are now required by law to include DfS in their design practices, which is a major modification to their traditional roles and responsibilities. Nonetheless, research shows that most designers lack the expertise required for effective implementation of DfS. This paper discusses the development of a mobile computing enabled knowledge management system that can assist designers to reduce accidents in the construction industry through safe designs. The system can provide modular and just-in-time knowledge support to designers during the design process. The utilization of the system could foster enhanced DfS implementation in industry and thereby accident reduction in construction projects.*

KEYWORDS: *Workplace health and safety, Design for Safety, Knowledge Management System, Mobile Computing*

1. INTRODUCTION

Accident prevention and control in construction is a continuing challenge. Despite many initiatives to improve safety, construction has one of the worst industrial safety records of all sectors, including high-risk industries such as chemical, mining, electrical and transportation (Hu et al. 2011). In Australia, the construction industry's accident rate of 22 per 1000 workers is much higher than the national rate for all industries of 14 per 1000 workers. Its fatality rate of 5.9 per 100 000 workers is almost three times the rate for all industries, which is 1.9 per 100 000 workers (Safe Work Australia 2011). This abysmal record is reflected elsewhere. In the US, for example, the construction industry accounts for 19% of all workplace fatalities and remains the highest source of fatal workplace accidents (Bureau of Labor Statistics 2010). In the UK, the construction fatality rate constitutes 21.5% of total workplace fatalities (Health and Safety Executive 2010) while reportable non-fatal injuries averaged 16 per 1000 workers, significantly higher than the overall average of 10 per 1000 workers (Labor Force Survey 2009).

Traditionally, safety has been the responsibility of builders who develop detailed safety management plans and implement them on site to reduce accidents. However, there is considerable evidence that decisions made by designers early in the development process have significant implications for the safety of workers on construction sites. Behm's (2005) research of 224 fatalities showed that 42 per cent of which were avoidable if design for construction safety concept had been applied. A report on design-related work injuries in Australia found that design-related issues contributed to 37 per cent of workplace fatalities and at least 30 per cent of injuries (Creaser 2008). Similarly, a detailed review of 100 construction accidents in the UK found that in almost half of all cases (47%) a design change would have significantly reduced the risk of injury (Gibb et al. 2004). Hence, designers have a role in reducing accidents in construction too. The concept of Design-for-Safety (DfS) has emerged from this argument and is a methodology applied by designers through the different phases of the design process to identify and mitigate safety hazards caused by design decisions.

Recognizing the important contributions which good design can make in improving safety performance, many governments around the world have been promoting DfS vigorously via a variety of mechanisms. Some governments have in fact mandated the use of DfS in their workplace health and safety legislations. Designers in many countries are now required by law to include DfS in their design practices, which is a major modification to their traditional roles and responsibilities. Nonetheless, industry surveys show that most designers lack the expertise required for effective implementation of DfS because their design degrees did not cover onsite OHS aspects adequately.

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Several resources claiming to support designers with DfS analysis are already available. Nonetheless, the industry is still faced with challenges for their effective implementation. Spiteri & Borg (2006) argued that designers constantly require *modular* and *just-in-time* knowledge support during the design process. *Just-in-time* implies that knowledge is provided immediately when it is required to ensure that correct decisions are taken at differing design stages. This knowledge has to be presented in a *modular* format, making it possible to structure the information required into components that can be translated into usable chunks, which can then be *reused elsewhere* in similar design situations. They further suggested that mobile knowledge management systems are ideal tools for providing the right knowledge within the right context at the right time to architects. Hence, the aim of this research was to develop a mobile computing enabled knowledge management system that can assist designers to reduce accidents in the construction industry through safe designs.

2. THE CONCEPT OF DESIGN-FOR-SAFETY (DfS)

In order to better manage and improve worker safety, there is a wealth of research to identify and understand factors contributing to workplace injuries. Traditionally, the design-bid-build model of proceeding construction activities led to the perception that ensuring the safety of construction workers is largely left to construction contractors (Hinze and Wiegand 1992; Rechnitzer 2001). However, in recent years especially the last two decades, taking safety into consideration well ahead of the start of the construction work has gained momentum. A frequently cited research by Szymberski (1997) illustrated the relationship between project schedule and the ability to influence safety, as shown in Fig. 1. This seminal work puts forward the concept that risks associated with a project are mostly determined at the conceptual stage of the project, whereas when the project reaches the actual construction stage little can be done to improve safety. Since then, attention has been paid to quantify the relationship between design and construction accidents.

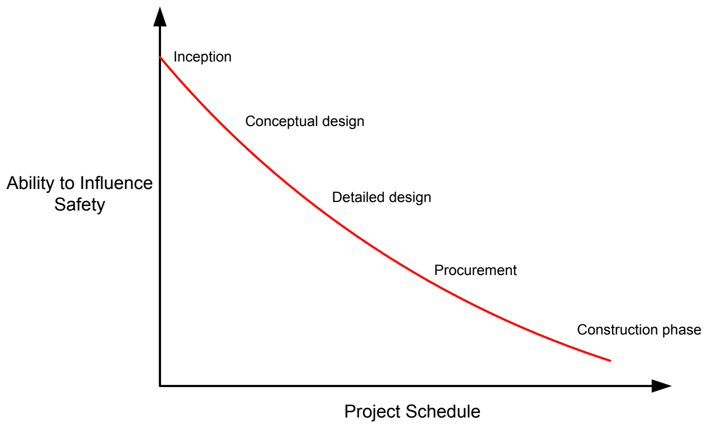

Fig. 1: Time vs Safety influence curve (Source: Szymberski 1997)

From the above discussion it can be seen that taking account of safety in the design stage is of vital importance in construction and hence the concept of DfS or design for construction safety has been formally proposed in research. According to Gambatese *et al.* (2005), "designing for construction safety entails addressing the safety of construction workers in the design of permanent features of a project". This means that DfS is a proactive prevention of potential hazards, in other words, it is directed at eliminating potential hazards at source before they outset; i.e., dealing with problems in the project design stage more than in the project implementation stage (Fadier and De la Garza 2006).

Concerning the benefits of DfS, the most notable and direct benefit is reduced hazards and thereby less accidents on construction sites. Moreover, three added benefits of DfS can be summarized as follows (Toole and Gambatese 2008):

- the proactive identification and avoidance of hazards in the design stage is considered safer and more cost effective than reactive management of risks in the construction stage;
- design professionals are more knowledgeable of technical issues, such as stresses and electricity in construction project. Therefore, the DfS concept of requiring this group to consider safety in their work can achieve better use of human resource; and

- DfS helps to raise awareness of safety in construction by including all entities, especially designers, in the effort to reduce construction injuries. This, obviously, has important implications for construction practices.

3. THE PROCESS OF DfS

DfS is an iterative process that is applied in different phases of design development, and involves a multidisciplinary team. Fig. 2 illustrates the various phases in the design process and how DfS is integrated into these phases. It also shows the stages involved in the DfS process.

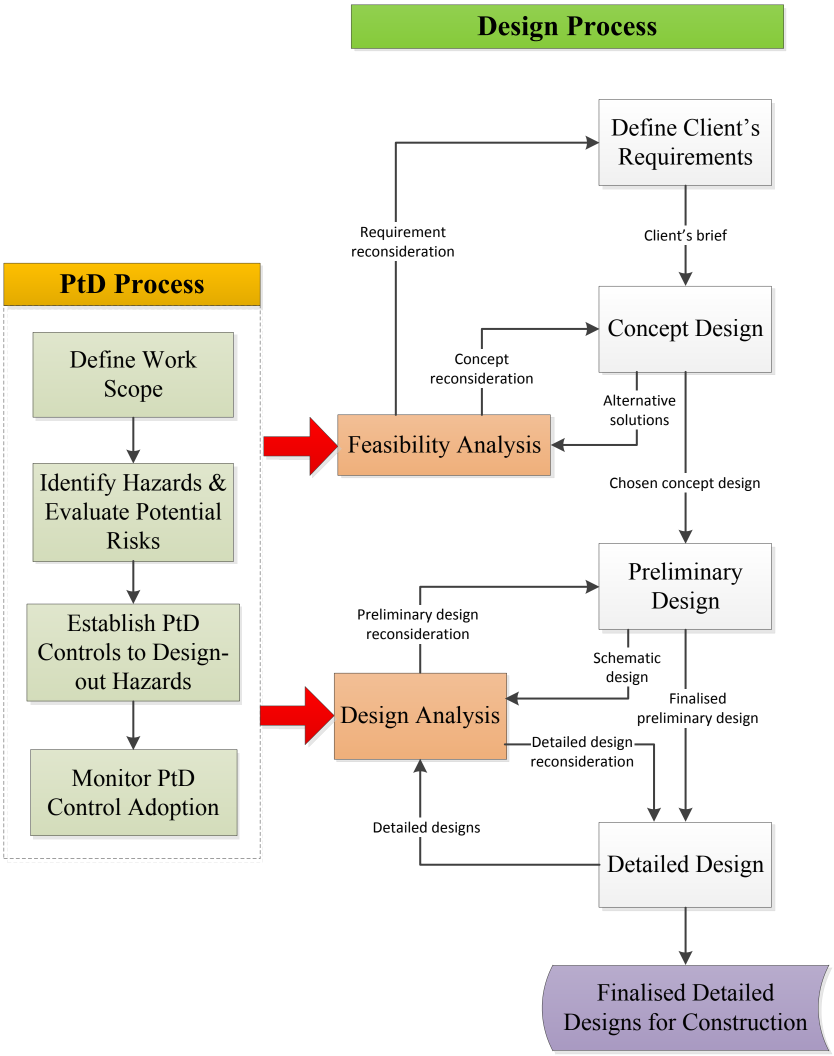

Fig. 2: DfS process

The design process begins by defining client's requirements. In this phase, the design team works closely with the client to determine the requirements for the project in terms of its functionality, performance level, design and aesthetic features and other characteristics such as sustainability, budget and time constraints. The outcome of this phase is a client's brief, which serves as a foundation for the remaining phases of the design process.

In the concept design phase, alternative project solutions to meet the client's requirements are identified. Following that, feasibility assessments of the concept proposals are accomplished with the aim of selecting the optimum project solution that is achievable, both technically and financially. Concept design DfS forms part of feasibility assessments. The objective of concept design DfS is to evaluate concept design proposals from a workers' health and safety perspective and to establish a safe design basis for a chosen concept design to carry on into the preliminary design phase. In this analysis, considerations need to be given to both the project site context and concept design alternatives. By establishing the relevance of the project context, advance thinking about possible hazards and safety implications to be provided and visibility to DfS considerations to be given from the outset. Consequently, concept level DfS suggestions are drawn for a preferred concept design, including: construction methods and techniques, orientation of the facility, use of prefabrication, types of temporary structures, types of materials and equipment, etc.

The chosen concept design is further defined in the preliminary design phase. An overall project configuration is defined whereby system and component level design requirements are established. Furthermore, schematic drawings, layout definition drawings and other engineering documentations are developed to provide an early project configuration control. DfS efforts in the preliminary design phase are an incremental of the concept design DfS. First, an audit on the preliminary design is to be undertaken to ensure that concept design DfS suggestions have been absorbed in reasonably. Then, a hazard analysis will proceed from a facility level analysis to system and component level analysis. The study of project scope and sketch designs will identify and analyze work trades to be involved in the project. For example, deep excavation, works at heights, manual handling, management of hazardous materials such as asbestos and waste, temporary works, erecting structures, crane use, works over water, confined space works, etc. Having identified the work trades and qualitatively analyzed potential hazards in the project, high level DfS suggestions will be made for risk control through preliminary design revision.

The detailed design phase produces different types of design drawings and specifications for components and systems (architectural, structural, MEP and Fire system, etc.), thoroughly describing their interfaces and functions so that they can be built on site. Detailed design DfS efforts analyse the designs and specifications of individual elements to locate hazards caused by design decisions. The risk analysis step will then determine which of the hazards are removable by design revisions and which are to be managed on site. Subsequently, DfS suggestion reports will be produced for design revisions. The risk monitor step will oversee how the DfS suggestions are embraced in revising the original designs.

4. REVIEW OF EXISTING RESOURCES FOR DfS

In order to implement DfS, designers must thoroughly know the construction contexts of their designs. Every design creates a construction context, which dictates the level of hazard posed by the design choice. The construction context can be usefully conceived of as including five elements: site settings – site terrain condition, space and accessibility, road and traffic condition and vicinity; task settings – location of the task and temporary structures/facilities needed to build it; materials – type and nature of materials used; equipment – type and nature of equipment used; and labor - type and skill level. A construction accident can emanate from one or a combination of the contextual elements. DfS must therefore perform a what-if analysis for all possible design options for a building project to take account of their construction contexts and make safe design choices, using an iterative process from inception through the detailed design phases. The critical challenge here is the skill gap of designers. Since designers are predominantly trained in design principles and they do not often work on construction sites, they usually have only limited practical knowledge of construction operations and contexts triggered by their designs. Detailed knowledge of construction technology, OHS and risk management is essential to undertake meaningful DfS analyses.

Several DfS resources claiming to support designers in DfS analyses are already available. These resources fall into two categories: frameworks that elaborate on DfS procedures; and tools that help to identify specific risks that can be addressed in the DfS process. Under the category of DfS frameworks: in Australia, Australian Safety and Compensation Council published Guidance on the Principles of Safe Design for Work while the WorkCover introduced the Construction Hazard Assessment Implication Review (CHAIR) (Mroszczyk 2008). The UK Health and Safety Executive (2010) also developed several documents to assist designers with DfS (see: http://www.hse.gov.uk/construction/cdm.htm and http://www.cskills.org/supportbusiness/healthsafety/). These resources provide an overarching working guideline for DfS practice. However, the procedures for DfS do not show how risks can be identified, addressed and monitored using specific measures in detail. Moreover, they are only paper-based guidelines and manuals for DfS. On the other hand, under the category of tools for risk identification during DfS practices, Hinze & Marini (2008) developed around 400 design suggestions, which were incorporated into a computer design toolbox, and Cooke et al. (2008) introduced a web-based system called ToolSHeD to help designers assess the level of fall risks in their design choices for roofs. The issue of risk identification and evaluation has been a particular focus of the second category, DfS tools, which provide a whole and more specific set of risk issues that can be addressed in the design stage. However, they do not really establish a safe design framework but serves as a supplement to existing frameworks. Very recently, building information modeling (BIM) tools have been developed to provide designers with DfS assistance (Zhang et al. 2013). Because BIM is still in the infantry stage of implementation in the industry, its high level application for DfS would require more time.

5. DEVELOPING A MOBILE KNOWLEDGE MANAGEMENT SYSTEM FOR DfS

It could be safety argued that designers would need an easy-to-use and economical DfS support resource, given the complex nature of the design process and the cost and time constraints design firms face. Recent advances in mobile computing technologies offer unique opportunities for developing cost-effective, novel knowledge management systems for the construction industry. The management of knowledge made possible by mobile computing devices (e.g. PDAs, Smartphones & iPads), together with mobile Apps, has critical aspects that best suit and appeal to designers as they can provide anytime, anywhere access to contents, just-in-time support and a media-rich interactive environment (Acar et al. 2008). Many construction-specific mobile Apps are already in use, ranging broadly from specific purpose calculators to design, collaboration and site monitoring tools (Mike 2011; ConstrucTech 2011). In contrast, and despite this proliferation, the potential of mobile computing technologies for accident prevention through design has not yet been explored. Hence, this section elaborates on the conceptual development of a new mobile App that can assist designers in reducing the high toll of construction accidents by prevention through design.

The conceptual design of the proposed mobile App includes a DfS knowledge map and mock-up layouts or wireframe diagrams. The knowledge map represents the logical layout of DfS knowledge and information for easy use by designers while the wireframe design outlines the placement of text, images, and buttons. These, together, conceptualize the proposed mobile App.

Fig. 3 illustrates the DfS knowledge map for fall prevention through design, a demonstration case. This was developed based on the findings of detailed content analyses of related documents and literatures, and comprises the design solutions needed for fall prevention through design. The map outlines the building elements considered for fall prevention and then detailed design solutions for one of the elements, roofing, are described.

Fig. 4 illustrates the wireframe mockup of the proposed mobile App. A number of wire framing tools are available for creating mockups and clickable mobile App simulations. Examples include Axure, Balsamiq, Fluid, Justinmind, Mockflow, Moqups, Proto.io, Protoshare, UXPin Wireframe. This mockup was created using UXPin.

6. CONCLUSION AND THE WAY FORWARD

DfS is regarded as an effective means to curtail workplace accidents on construction sites as it eliminates hazards at source. Designers face numerous challenges in effectively implementing DfS in their design practices owing to their limited knowledge on construction safety. This research has demonstrated how a mobile App can be developed to assist designers in accident prevention through design. Nonetheless, the paper discussed only the design part of the mobile App. Further research is underway to test the effectiveness of the new mobile App to support effective DfS analyses. In conclusion, the implementation of the new mobile App, after testing, could foster enhanced DfS implementation in industry and thereby accident reduction in construction projects.

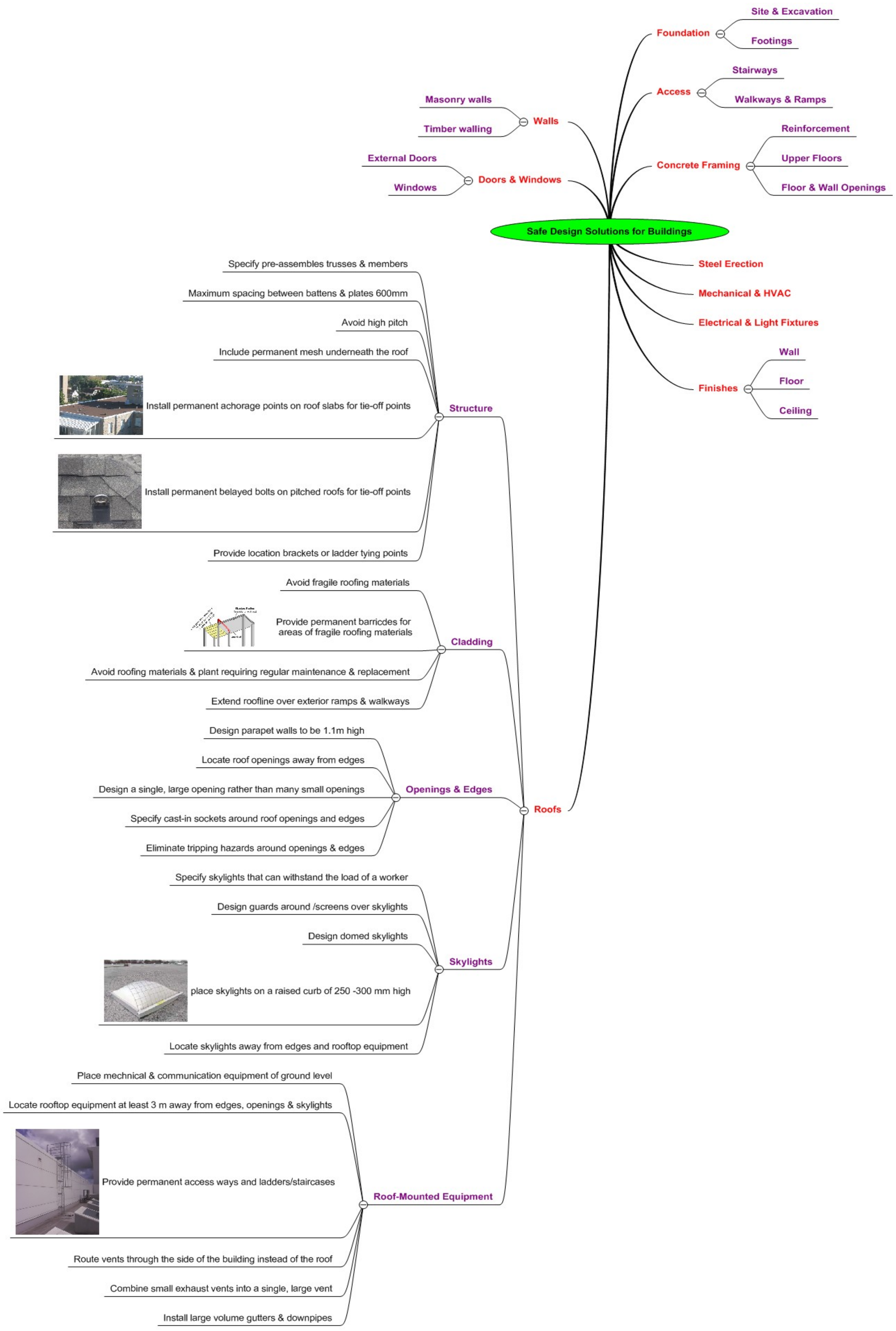

Fig. 3: Knowledge mapping for fall prevention through design

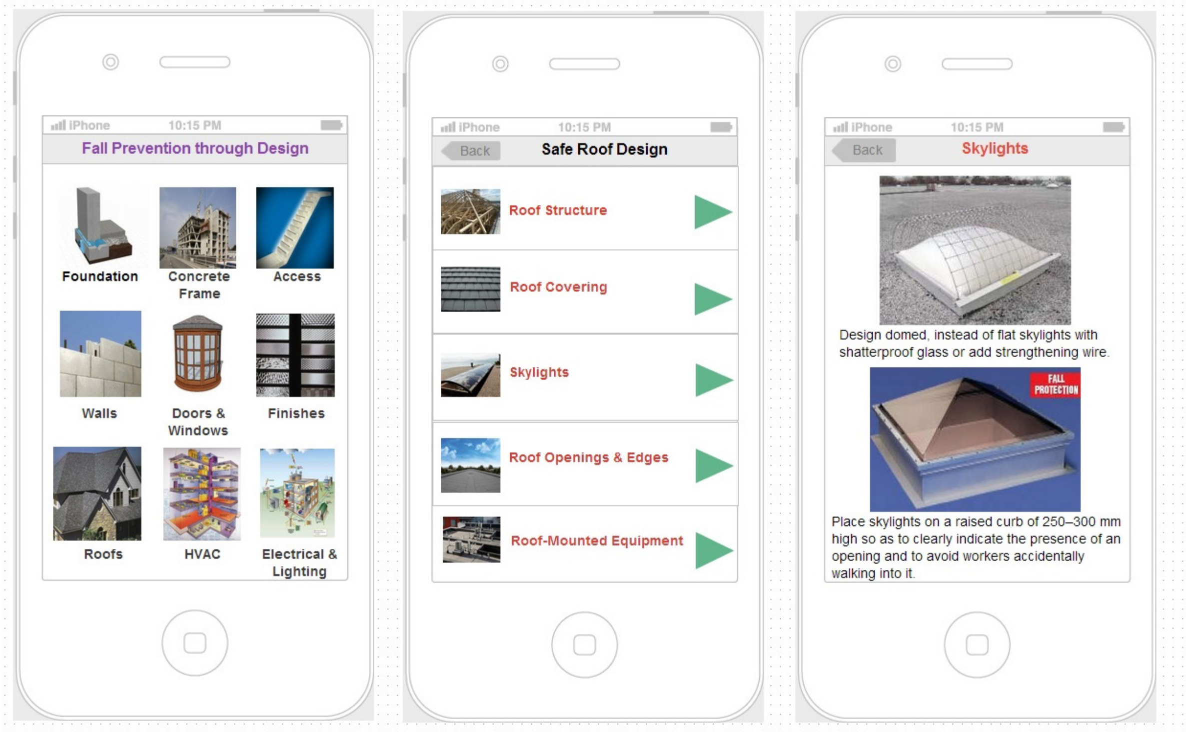

Fig. 4: Mobile App mockup for fall prevention through design

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