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Safety by design: dialogues between designers and builders using virtual reality

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Designers can contribute to enhancing the safety of construction work by considering how their decisions impact on both the physical environment in which construction workers operate and the means and methods they use. To do so, however, designers require knowledge about safety hazards on site and the opportunity to examine their designs early in projects. Through a set of studies virtual reality tools were used to examine the potential for collaborative dialogue between designers and builders to provide a forum for learning and proactive change of a design to make a project safer to build. In the tests, participants viewed proposed designs using virtual reality to examine various alternative design and construction scenarios. The study shows that consultation and dialogue with an experienced construction professional are highly beneficial for designers to appreciate the implications of designs on safety, and that designers are more willing to adapt design details than to change aesthetic aspects of their designs.

Keywords: Building design, construction safety, engineering design, virtual reality.

Introduction

Despite significant improvement in recent years, the rate of accidental death for construction workers is still high. In the UK, the annual rate has dropped from a range of six to eight per 100 000 during the 1980s, to a range of two to three per 100 000 since 2010 (HSE, 2013). In Israel, it has dropped from approximately 20 to 12.7 per 100 000 over the same time period (MoITE, 2013). Although most studies seek causes and propose improvements that are focused on the construction stage, research cited by the UK Health and Safety Executive (HSE, 2003) judged that 'up to half of the 100 accidents could have been mitigated through design change' (HSE, 2003, p. 72), with the detailed investigation finding that the permanent works design was related to the incident in 25–47% of accidents (HSE, 2003, p. 214). Behm's analysis of 224 fatal accidents from the National Institute for Occupational Safety and Health (NIOSH) Fatality Assessment Control and Evaluation (FACE) database found 42% of the accidents to be associated with design factors (Behm, 2005), a proportion which Brace *et al.* (2009, p. 56) indicate concurs with the work of Gambatese *et al.* (2008).

These figures reflect the fact that because the design team determines the final shape of the building and selects the materials that are used, its decisions have direct bearing on the selection of construction methods and processes and of the maintenance systems that are to be used throughout its lifetime. Because design configures the topology and topography of the physical environment in which people work, designers play a central role in determining the relative safety or danger inherent in the work (Brace *et al.*, 2009). Dharmapalan *et al.* (2014) researched the relationship between design features of multistorey buildings and were able to evaluate the relative safety risk inherent in each of the different alternative design features.

The 'safety decision hierarchy' (Manuele, 2003) prioritizes elimination of a hazard by means of changing

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the design of a product. The sequence, also known as the 'hierarchy of control', lists the following approaches to improving safety: elimination through design, substitution with less hazardous materials or methods, engineering controls (safety devices), warnings, administrative controls, and lastly personal protective equipment with the lowest value. The US National Standard for Prevention through Design (ANSI/ASSE, 2011), which deals with product design in general, emphasizes and applies the notion of elimination through design. Architects and structural engineers typically give high priority to elimination of hazards to occupants or users of buildings, but they appear to be less conscious of the need to apply the same thinking to the construction process.

Thus the goals in the current work are to test designers' knowledge of and attitudes to construction safety hazards and to explore the possible efficacy of design reviews for construction safety performed by designers in collaboration with construction professionals. We test the possibility of improving design through cooperation between designers and builders (in this context improved design means design that allows for safer construction methods than the original). The idea is that through enhancement of the interaction and dialogue between designers and builders when evaluating the construction methods needed to implement any given design, designers would increasingly be able to bring safety considerations to bear in selecting design solutions.

The basic hypothesis is that designers can contribute to the safety of construction sites. Designers, however, often lack practical experience in construction and maintenance (Raviv *et al.*, 2012), which makes it difficult to include safety considerations in the early stages of the design process. Construction professionals, on the other hand, have ample practical experience in construction methods, which includes knowledge acquired 'the hard way' by solving problems on the job.

We report on a research programme comprised of a pilot study and a main set of tests, using a Cave Automated Virtual Environment (CAVE) and two virtual construction sites, to examine the potential of collaboration between design teams and construction teams to contribute to achieving a building design that would be safer to build. In each collaborative dialogue in our experimental work, participants toured a virtual construction site that showed a building under construction. The virtual reality (VR) environments offered designers the opportunity to experience safety hazards under the guidance of a construction professional and to initiate collaborative discussion following which design alternatives were suggested for the dangerous situations identified. Taken together, these studies begin to answer the following questions:

- Can a dialogue with construction professionals, conducted while touring the virtual site, improve designers' awareness of and sensitivity to hazards?
- Can the risk inherent in a construction project be minimized by enhancing designers' awareness and understanding of safety issues?
- To what extent are designers willing to change design in order to enhance safety?

The next section outlines the previous literature on designers and worker safety. The following section discusses experimental design and the methodological learning across the pilot and the full-scale studies. Thereafter results from both the pilot study and collaborative designer–builder design safety reviews are described. The discussion section draws insights from the results and comparisons with the findings of other experiments. The conclusion section summarizes the main contributions, and provides recommendations for promoting safety and for further research.

Designers and worker safety

Hinze and Wiegand (1992) conducted one of the first studies to address the role of designers in construction safety. They found that less than one-third of design firms even addressed the issue of worker safety during the various design stages and claimed that a basic change was required in the perception of professionals in the various design disciplines. Szymberski (1997) claimed that the ability to affect site conditions that have implications for construction safety is weakened the closer the project is to the construction stage, and that important opportunities lie in the conceptual design stage and in the early design stage. Gambatese (2000) found that in all that pertains to safety, designers usually focus on the intended occupants of the planned office or residential building, rather than on the construction workers.

In the US, NIOSH published inquiry reports on 500 fatal accidents (NIOSH, 2009). Behm (2005) examined 224 of those reports and concluded, based on statistical analyses, that up to 42% of the accidents could have been prevented had the safety design concept been implemented originally. Atkinson and Westall (2010) identified several practical steps that designers can take, including finding out what construction method the contractor plans to use, the recommended size of components for safe installation, time coordination of work so as to ensure safe

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construction, and ensuring the contractor understands the design rationale. However, the traditional 'design-bid-build' method of procurement creates a complex hierarchy of contractors and subcontractors, separate in time and responsibility from the design, limiting designers' understanding of means and methods and their influence on these through the design of the permanent structure.

However, the legal responsibilities of designers and contractors affect attitudes to construction safety, and in some countries, such as the US and Israel, the legal system raises barriers to designers assuming responsibility for the safety of construction workers. According to US practice, as guided by Occupational Safety and Health Administration (OSHA) regulations, responsibility for worker safety in construction is borne by the contractor alone (Gambatese *et al.*, 2008). In this context, the concern over legal liability causes designers to recoil from taking on an active role when addressing construction safety (Gambatese *et al.*, 1997, 2005). By contrast, in the UK the responsibility for safety is collective and includes all who are involved in the construction project. The direct responsibility for coordination of the safety efforts is assigned to the 'construction (design and management) coordinator', and the legislation details the managerial actions that they must take in order to ensure proper consideration for safety in design and collaboration between all the responsible parties (CDM, 2007).

Another aspect of the effect of design on construction safety is the frequency of design changes during construction. A study conducted on a large construction project in a London train station revealed that the volume and frequency of design changes led to real difficulties in planning safe work, particularly when working at heights, lifting of especially heavy elements, and renovating and demolishing old structures (Larsen and Whyte, 2013). In this case study, the researchers also found that despite new UK legislation (from 2007) that included designers in the responsibility for safety, with the new role of a construction (design and management) coordinator, the site managers felt architects continued to regard the building's aesthetics as the decisive factor that prevented their consideration of construction safety.

In order to play a useful role, designers must acquire the knowledge and understanding of how health and safety risks and hazards appear in construction and how design may prevent or minimize them (Baxendale and Jones, 2000). With few exceptions (such as those involved in design-build contracts), designers lack the expertise and practice required in order to address construction safety issues (Zhou *et al.*, 2012). Many designers claim that their education and professional training fail to prepare them to address construction safety and that no tools are available to help them improve design so as to enhance safety (Gambatese *et al.*, 1997).

In an attempt to fill this void of design tools, Gambatese *et al.* (1997) compiled a booklet titled 'Design for Construction Safety Toolbox' as part of a research project conducted on behalf of the Construction Industry Institute (CII). The booklet presents over 400 design suggestions for improving design to promote construction safety, covering various design disciplines, construction site hazards, construction site types, building components, and building methods. The recommendations were collected from a literature survey, interviews with experts, instruction manuals, and checklists.

Previous studies also identified shortcomings in the construction industry in the transfer of knowledge from the field to the design firms. Collaborations between designers and construction professionals in general, and attempts to improve safety in particular, have failed due to a clash between the approach adopted by designers of learning from written material (reports and documents) and the approach advocated by field professionals of learning through trial and error (Gherardi and Nicolini, 2000; Rooke and Clark, 2005; Styhre, 2009). To overcome this obstacle we propose using VR technology to facilitate a dialogue on safety issues between the design teams and the construction teams. Visualizing the final product is at the heart of the design process and VR technologies enable designers to simulate the design products (Whyte, 2002). From the perspective of construction safety, however, the design of the process is often more critical than the design of the product itself. The power of simulations that afford an understanding of safety aspects is manifested in a series of DVD films produced in England by the Royal Institute of British Architects, entitled 'Safeguarding People: Achieving Design Excellence' (RIBA, 2009).

The computer software 'Design for Safety Process Tool', which was developed for personal computers (Hadikusumo and Rowlinson, 2002), offered a basic application for presenting construction processes for safety and risk assessment by designers. This is limited because in many cases safety issues are dependent on specific contexts that change over time, and thus require the tacit knowledge of construction experts to identify them. Rozenfeld *et al.* (2007) identified loss-of-control scenarios that commonly occur in a variety of construction activities and showed how they can be used in a construction information model to identify the exposure of workers as a function of time, and implemented the approach in a software prototype called CHASTE. However, a numerical analysis of the kind that exists in the CHASTE system does not give indications of the design characteristics that led

to the said safety hazards, nor does it offer safer alternatives. The methods developed in this study have three drawbacks: (1) they rely on automation to identify and display the hazards from a database, and do not enable the user to identify dangers as they develop; (2) they did not involve designers at the experiment level; and (3) they are only suitable for the later stages of the design process when most of the design decisions cannot be easily changed.

Thus none of the research studies found in the literature contemplated engaging designers and builders in a dialogue focused around their specific project with the goal of improving the design in terms of its impact on construction safety.

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Methodology and experimental design

The methodological approach was to qualitatively explore designers' knowledge and attitudes by eliciting their responses in conversations that used a building design presented in a virtual construction site as an artefact to stimulate discussion. The pilot study and the main set of tests differed as regards the roles played by the construction professionals who were party to the conversations and they varied as to the number of replications performed. Detailed analysis of the recordings from each of the experimental dialogues in the pilot study in turn not only provided new insights into the potential for improving safety through the type of design reviews that were simulated, but also led to successive improvements to the experimental design itself. These were implemented in the main series of tests.

Researching the potential for engaging designers in discussion with builders required a construction site context in which safety hazards could be clearly understood by participants but without exposing them physically to the hazards. The need to replicate experiments with numerous participants while holding all other parameters constant, and the need to record conversations, led to the decision to conduct the simulated design safety consultations using VR to present the building designs under discussion.

The method adopted for all of the tests, using a virtual construction site to explore the potential of collaboration between designers and builders, is innovative in the context of construction safety. It facilitated exploration of designers' attitudes and knowledge, and the possibility of learning. This has many advantages over alternative methods such as questionnaires and interviews. The details of the method were developed and improved through the different stages of the research, starting with the pilot collaborative sessions using a CAVE and culminating with the series of CAVE experiments with 10 professional designers. The need to isolate and compare multiple designers' responses also led to the decision to fix one of the variables by employing the same expert builder across multiple dialogue sessions with a range of designers. The role of the building professional in the main study was played by one of the researchers, who had 30 years of experience on site, whereas in the first two pilot study tests both roles were played by research participants. Using a 'constant' building professional creates similar conditions across these dialogues, focusing attention on the responses given by each of the designers. It allows both qualitative and quantitative comparison of designers' attitudes, skills and potential for learning and change.

Pilot study of safety dialogue in a CAVE virtual construction site

Two pilot tests were conducted with industry participants, in which they initially did an independent individual design review assessment, and then engaged in dialogue within a virtual construction site, which was simulated in a CAVE. The first test was performed with three members of the engineering modelling and visualization consultancy firm that had provided the model. One was an experienced construction manager (a 'builder') and the other two were designers. The second test was performed with two construction (design and management) coordinators[1] from a major construction contractor. These professionals each had relevant knowledge of both design and construction as they both had design backgrounds (one in architecture and the other in civil engineering) and they had worked on site safety issues for more than 10 years. This second test provided data on how experts navigate and discuss safety issues in a model rather than designer–builder dialogue. These two pilots provided the research team with substantial input on how to set up VR models and conduct dialogues with builders and designers.

In the pilot work, we sought to understand whether the virtual environment adequately replicated the actual environment and whether experienced users identified these safety issues. By having participants first view the model individually on a desktop computer and identify the hazards they saw, we were able to understand what new information became apparent through the use of the CAVE. Individual assessments were recorded in note form and the dialogues were recorded, transcribed and analysed, with the first test used to check scenarios and refine the process for the second test.

In preparation for the pilot tests, the building geometry was imported and translated from the provided 3D model. Following a review of construction

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safety statistics, nine example scenarios were created by researchers with reference to commonly identified issues on construction sites (falls from height and vehicle movements). These were low parapet; closely spaced openings; missing guardrail around the roof access; steep roof pitch; missing fall protection; missing covers over exposed openings; no attachments or holes in structural members for attaching harnesses; missing foot boards on a scaffold; and a moving crane with load where workers are present. These scenarios included elements of permanent design and temporary works. They were added to the model with the intention that they provide a starting point for discussion with the participants in the pilots. The CAVE used is 3 3 m square with images projected on to the floor from above, and three 2.2 m high walls with rear projected images. Users wear 3D stereo glasses. Figure 1 shows the subjects inspecting the scaffolding in the CAVE.

In these pilot tests, a researcher served as 'navigator' for participants, using a hand-held joystick to perform a 3D walkthrough, viewing the construction site from the positions or angles requested by the participants. A virtual pointer controlled by the lead observer was also provided, and this was free to be used to highlight areas of interest and assist collaborative discussion. While participants could walk freely through the model, by instructing the navigator, a viewpoint was set up to give the participants a good view of each safety scenario, with animation added in the set-up of the final scenario with a moving crane. Buttons on the joystick were used to switch the users between different viewpoints and different phases of the construction.

The tests were recorded on video using a camera set up outside the CAVE. The footage captured the collaborators' conversations, their interaction with virtual objects in the model, and their behaviours. The utility of setting up a 3D model with viewpoints, animations and potential modifications were discussed during and after both pilot tests.

Designer-builder safety reviews in a CAVE virtual construction site

In this main study, design professionals were brought to a virtual construction site and participated in a tour guided by one of the authors, a construction engineer with some 30 years of experience on site. This engineer played the role of the 'builder' in the designer–builder dialogue. Ten architects and structural engineers each participated in a tour that required approximately 90 minutes. During the site tour, they encountered 32 scenarios of construction hazards directly related to the building's design that were modelled in the virtual site. They were asked to discuss the construction aspects and safety considerations in general with the builder. They were also specifically asked about their influence as a designer on the creation or prevention of each risk. The tours were recorded in video and in audio. Analysis of the participants' reactions to the problems afforded an understanding of their basic approach to the specified issues and enabled measurement of their learning through dialogue with the building professional.

A high-rise residential project was chosen for the virtual construction site because a large proportion of the recorded accidents are falls from height or involve



Figure 1 Safety professionals inspecting a scaffolding scenario in the CAVE

falling objects. The project comprised two 28-storey buildings with four apartments on each typical floor. Each of the two buildings was modelled at a different stage of construction and featured lobbies with two-storey ceiling heights, typical apartment floors, penthouse apartments with roof grades, and a utility roof. The construction stages that were examined included structural works, installation of mechanical, electrical and plumbing (MEP) systems, interior finishing works and façade finishing methods such as curtain walls and stone cladding. The model included a tower crane, temporary construction railings on balconies and interior staircases, formwork for concrete pours, unfinished structural elements with exposed rebar, ladders, scaffolding for interior MEP work, palettes of stored construction materials, and more.

The collection of scenarios simulating risk situations was chosen based on Gambatese *et al.*'s (1997) 'Design for Construction Safety ToolBox' and on statistics published by the Israel National Insurance Institute on construction work-related accidents, with an emphasis on risk situations that cause the majority of injuries in the industry (Bar, 2011). Figure 2, a page from the manual prepared for the experiment, provides an example of one of the scenarios. The example concerns the need to perform work at height for longer than necessary durations given the need to assemble the screen *in situ*, as opposed to prefabricating screens in large sections.

The ToolBox design recommendations relevant to the local context were identified and selected for modelling according to three main criteria, as follows:

- Relevance for the studied target population. The participants were architects and structural engineers; design recommendations that are relevant only for designers in other areas were not selected.
- Relevance of the design recommendation with reference to data on the frequency of occurrence of common accident types. The rationale of this criterion was the desire to make the risk

No. 15	Façade with visual barriers for laundry balcony	Model view: 3.4	Activation key in EON: F
Description :	Ianstallation at considerable height of a screen witha large number of components that require cumbersome installation, instead of prefabricating a single large element, designed to cover several stories, for safer installation.		
Key question:	Do you think this situation is justified? Have you ever implemented safer solutions in the past? Why not use aready-made element at least one story high?		
Design stage:	Construction detailing	Design category :	Fabrication details

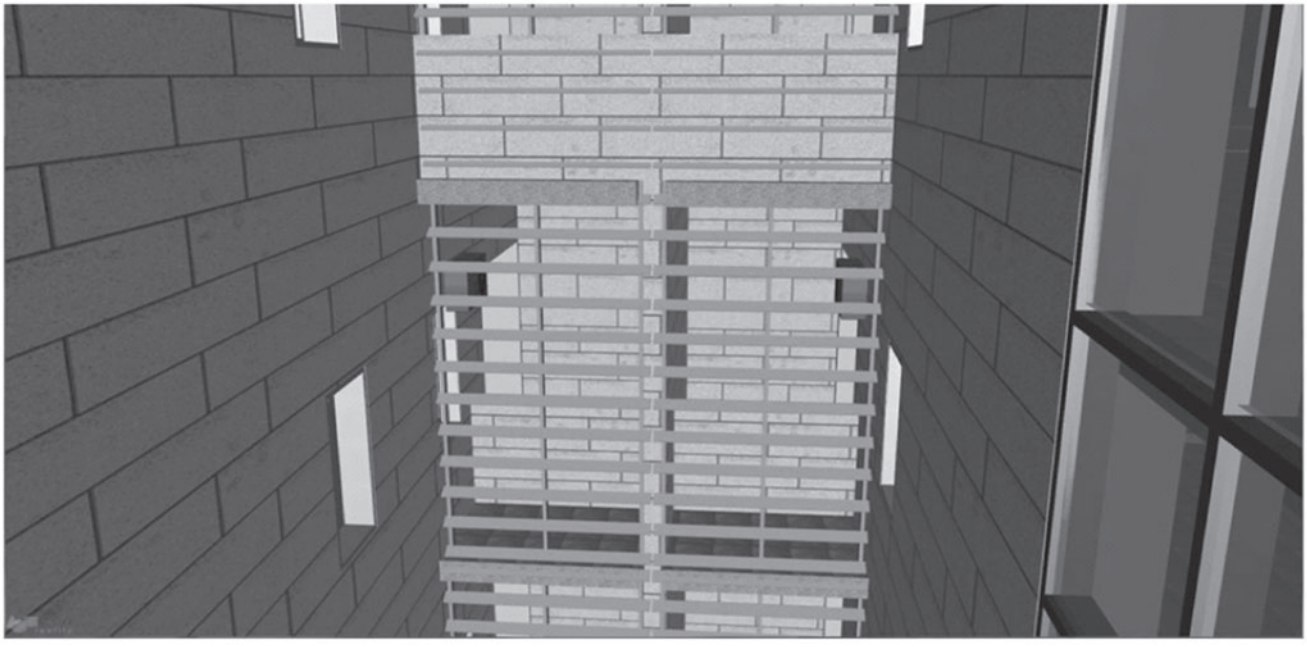


Figure 2 Example of an unsafe design scenario embedded in the virtual construction site model

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Table 1 Examples of translation of design recommendations into risk situations in the virtual construction site model

No.	ToolBox chapter	ToolBox design recommendation	Location in model	Method of presentation in the model
1	General conditions: special provisions	Minimize construction site visitation and public access through or adjacent to project site	Access road	The model comprises two structures: one is at occupation stage and the other is under construction. The access road to both buildings is within crane range, such that the crane oversails the public access route
2	Project component: technical specifications – steel	Limit the lift height of steel (or prefab concrete) erection	Roof	A steel pergola is modelled on the roof. Show two construction options: one with convenient support and screwing details, and the second with onsite welding without support details
3	Project component: work schedule /sequence – stairway	Schedule permanent handrails to be erected along with the structural steel as one assembly	Entrance lobby	Show a staircase with temporary handrail in entrance lobby. The permanent handrail is made of steel and is scheduled to be delivered only during the final stages of construction
4	Project component: work schedule/ sequence – elevated work	In multistorey buildings, schedule the exterior wall structure and/or finish to go up with the structure or soon thereafter	Façade	Two situations are modelled: (1) Curtain walls whose installation begins only after 20 floors are built with temporary railings on each floor. (2) A curtain wall whose installation takes place in modules of up to 3 storeys whereby each floor is closed as the work progresses
5	Project component: structure plan/ elevation – mechanical	Position control valves and panels away from passageways and work areas	Typical floor	A situation is modelled in which a water valve is located at head height
6	Project component: slab-on-grade, floor, roof	Design a permanent guardrail that surrounds every skylight	Roof	Two situations are modelled: (1) Skylight elevated by concrete parapet that is high enough to prevent workers from falling. (2) Skylight on roof level, without protection against falls. In both cases the glass in the skylight is missing
7	Project component: furnishing, finishes – ceilings	Minimize the complexity of construction of ceiling systems	Lobby	Installation of complex lighting fixtures in atrium lobby ceiling

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scenarios in the model relevant for local builders and designers. About 30% of severe accidents in construction in Israel result from workers falling on the work level or from a height and some 20% are cause by collision with a stationary or moving obstacle (Bar, 2011). The risks included in the model reflect these kinds of accidents.

- Practicality of representation in the model, taking into consideration any changes and adaptations needed to the model.

Table 1 gives several examples that illustrate the translation of a design recommendation into a risk situation in the model.

Once the design recommendations had been selected, the building model could be prepared such that it incorporated appropriate situations. Preparation of the model involved the following technical steps:

(1) Modelling using REVIT software. Figure 3 presents isometric views of a typical floor and of one tower made up of typical floors. The complete model was composed of several basic models of this kind: parking garage, entrance floor, typical residential floor, penthouse floor, and roof.
(2) Importing the REVIT model into 3D Studio and modelling of the construction equipment

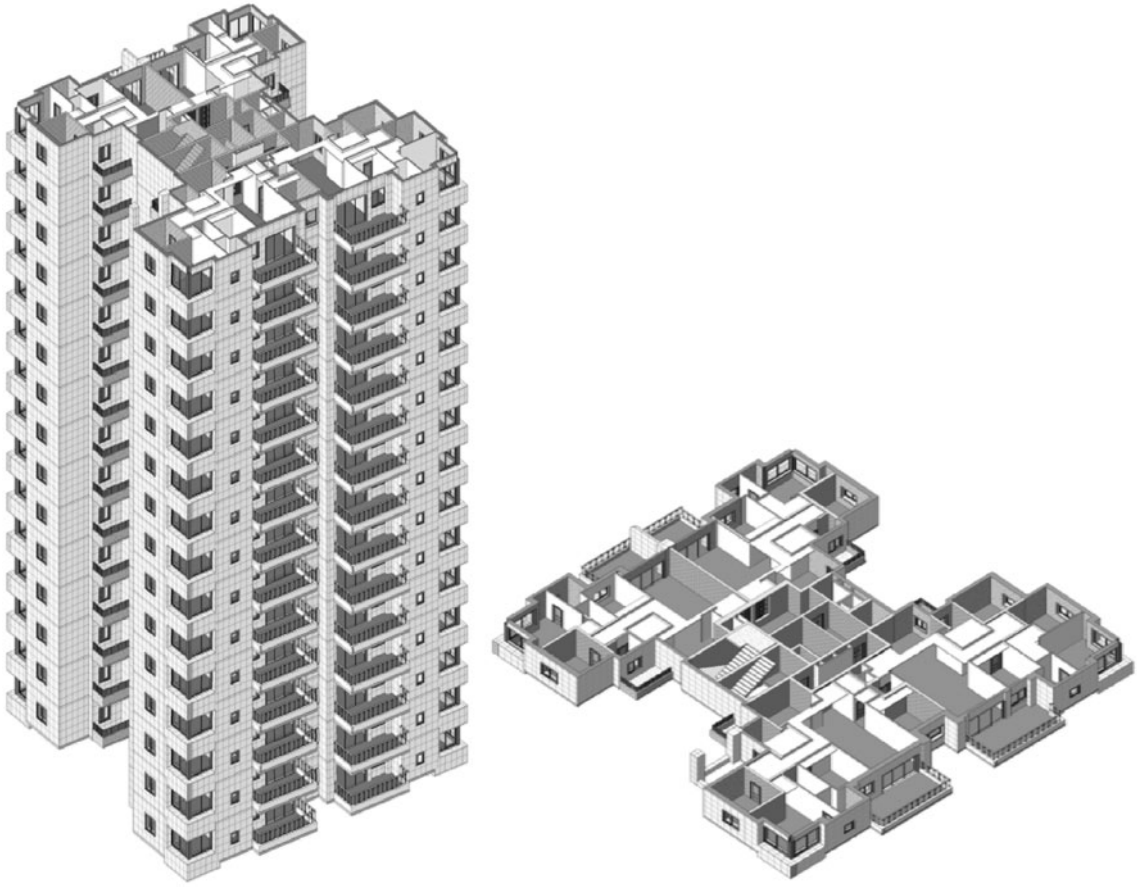


Figure 3 Constructing the model: replicating a typical floor plan

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(crane, formwork, shoring towers, scaffolding, etc.) and details that did not appear in the design drawings (interior air conditioners, vehicles, etc.), including modelling of the various risk situations.

(3) Importing the model into EON Studio software using EON Raptor, a designated exchange tool. Animations and other embellishments, such as addition of an urban environment background, lighting and moving vehicles, were implemented in EON Studio.

(4) Display of the virtual construction site in a three-sided CAVE using EON Viewer software with active stereo goggles and joystick navigation. To simplify the navigation and avoid the overhead time required in each replication of the experiment, a standard path through the model was prepared. The path included a fixed sequence of 'stations' at which the designers were to stop, look around, and observe the structure, the building activities, and the risk situations. The structured sequence of the locations had the added benefit of simplifying data analysis of the recorded conversations.

Preparation of the model was followed by extensive review to identify and correct any modelling errors that might distract the subjects. Only after thorough review could the series of review sessions with subjects begin. In the sessions, the researcher who played the part of the construction professional in the experiment did not write down the participants' answers during the experiment in order not to disrupt the continuity of the experiment or affect the authenticity of the dialogue. Instead, the audio recordings were later transcribed and documented by risk situation, whereby the participants' reaction was recorded alongside each risk situation in the model.

The dialogue transcriptions were analysed with respect to the following aspects: identification of the risk situation as unsafe for workers, general reference to the risk, and the recommended method of handling the risk/hazard. Table 2 presents the classification of the designers' responses. Classification was performed

Table 2 Classification of designers' responses

Issue	Classification of designers' responses
1. Does the designer identify the situation as a safety hazard for workers?	Yes Partially No
2. The designer's opinion of the risk	Situation is not dangerous Situation is not dangerous provided appropriate means are taken/work is executed according to procedures Situation is dangerous Situation is very dangerous
3. Recommended way of handling the situation	No handling necessary The issue is a design consideration of another designer/consultant, not within my area of responsibility My design consideration supersedes, and so protective measures must be taken The design should be changed for safety reasons to minimize the risk. The design should be changed for other reasons (maintenance, aesthetics) as well as for safety reasons The issue involves the builder's considerations; I would not dictate another solution

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by one researcher and was validated independently by two additional researchers. Although appropriate actions were taken to neutralize the assessors' subjectivity, it cannot be said that the analysis is completely unbiased.

Results

Dialogue in a CAVE virtual construction site: pilot study

While the participants in the pilot studies identified scenarios that the research team had introduced into the model, their dialogue was broader ranging. The experienced professionals in the first pilot test brought up a range of issues, some but not all of which related to the scenarios modelled by the researchers. In the second test, the discussion of the 3D model in the CAVE focused on major issues around: (a) the voids on the middle floor; (b) stairs; (c) scaffolding and cladding; (d) crane; (e) roof; and (f) voids and edge protection on the roof. The issue of edge protection was raised right at the beginning, before the research team moved to the first scenario, and was returned to multiple times through the conversation. Aspects questioned and discussed by safety professionals are summarized in Table 3. At this stage we identify hazards that participants discuss, and outline the nature of their discussion, rather than seek to identify particular solutions.

An independent assessment preceded this pilot, and in this the CDM coordinators both separately identified four of the hazards added to the model (low parapet; lack of anchor points; missing covers; missing guardrail); one of the two identified another (board missing on scaffold). As participants confidently identified and resolved some of the nine hazards individually, Table 3 focuses only on areas that they discussed in detail in the dialogue in the CAVE. Only once together in the CAVE did they mention issues related to, but not specifically, the remaining four (closely spaced openings; steep roof pitch; missing fall protection; moving crane with load where workers are present). Their independent assessments also covered a range of other issues that the research team hadn't considered, such as the influence of weather on site layout, which they each raised independently; and the potential to install the permanent handrail as the guide rail on the stair, which was again independently raised by both participants. Two issues identified were with the model (viewed on the desktop for these individual assessments), and included a missing brace between the main structure and the independent gate, which was an error in the supplied design model; and missing footing support for the scaffolding that the research team added.

Some of the time taken in the experimental dialogue in the CAVE was spent in basic familiarization with CAVE functions; discussion of modelling issues; swapping models and navigation. Twenty minutes were spent viewing the middle and top floors and roof of a static 3D model, during which participants identified the issues summarized in Table 3. Following the viewing of the 3D model, the next 10 minutes were spent on a 4D model: initially the whole sequence was viewed and then researchers revisited the sequence again, prompting the participants to discuss different aspects of the model and revisit and discuss issues. Finally three

Table 3 Identified risks and aspects questioned and discussed by the safety professionals in the second pilot

	Areas with risks	Discussion duration (min:sec)	Summary notes on aspects questioned and discussed (including short direct quotations)
a	Voids on the middle floor	5:23	Unprotected voids, sense of scale, technique for managing voids dependent on span, if permanent void might put permanent barrier up as part of construction, shaft all the way through, useful, see how voids connect
b	Stairs	1:55	Why is that open? No reason, or if there is a reason, it needs edge protection. Why can't you access throughout the building using the stairs which are part of the permanent design? Could change the design, bring those walls up with the structure, gives you protection at the same time
c	Scaffolding and cladding	3:24	Edge protection, how would you tie it into the building? Some sort of brackets to finish the cladding, void that things are dropping through. How are you going to get it up with the scaffold tied in? Add set-out lines for the lines of the cladding panels work out where the scaffold ties need to go. Ladder access up the scaffold, instead permanent stairs and scaffold lifts, accessed through the buildings. Work area access from outside
d	Crane	1:50	Now on the roof, issue with the crane becomes very obvious, lack of vision. Crane operators can't see what they are doing. No reason couldn't have a tower crane up through the middle, tower crane operator sitting above the project with a bird's eye view, better access
e	Roof	2:15	How would that be finished? [Prefabricated, manual labour] huge issue there. Could crane it on. There would definitely be a case for building in edge protection. Do we know if this is an open courtyard?
f	Voids and roof edge protection	4:40	Would have rebar through that, don't know what they are for. Fencing enclosure but these not within it. What are the openings for? Air-con. They are outside the safe area. Louvered barrier, part of installation. Need to understand it. What is obvious is, if that could be moved over it could provide a barrier without the need for temporary 'man safety' measures. For any new building you shouldn't have to have any 'man safe' in place. You probably want to ask the designers why you have all these voids, half a dozen 9" circular holes. May be oversizing them as they are not sure of the detail

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minutes were spent specifically on the operation of the crane.

In the dialogue, the participants identified areas in which they would like more information from, or to request changes from, the designers. They sought solutions where the permanent structure could be built safely without the need for additional temporary works for safety during construction, as summarized in Table 3. For example, on the voids on the middle floors (risk a), they considered running the rebar through the hole or installing the permanent barrier as part of the slab construction. They articulated the potential to use the permanent staircases (risk b) for circulation during construction, rather than having lifts or ladders in scaffolding (risk c); and the benefit of prefabricating a roof of this size (risk e). Although they did not explicitly mention the standard hierarchy of controls, their discussion revealed a clear preference for elimination of risk through design (obviating the need for temporary structures wherever possible) over engineering controls (such as running rebar mesh through holes or using permanent stairs rather than temporary solutions) and over the use of PPE, in that order.

The style of language used by the safety professionals shows a careful awareness of the limits of knowledge, where comments may be prefaced with phrases such as: 'don't know if this is relevant' and the dialogue moves between the professionals as safety issues are collectively explored and discussed. Issues such as the voids, which had been identified in the individual assessments were reconsidered when viewed at full scale in the CAVE virtual construction site, with one participant noting that 'I tell you what this does better than anything else, it gives you a sense of scale' before explaining that the holes were too large for the use of rebar; and a different solution was required.

The practical experience of the safety professionals also enabled them to consider options that were not visible in the virtual model. For example, they noted that in the modelled scenario the crane operator had an inadequate view of the site and hence would not be able to safely construct the roof (risk d). They considered alternative types of cranes, agreeing that the best in this situation would be a tower crane located in the courtyard within the building. As part of a discussion about the potential for prefabricating the roof,

the participants noted that with a tower crane in the atrium the crane operator would get a bird's eye view of the site and could stay located in one position and reach all points of the roof.

This first set of scenarios used in the pilot tests was rather simple, with some scenarios related to construction management issues rather than core design issues (e.g. missing temporary handrail, missing toe boards from scaffold and moving crane with load). While the many interrelationships make it difficult to separate the design of permanent and temporary structure, through this pilot work we clarified the different design scopes of the scenarios, with some focused primarily on permanent design and others on temporary design. This work informed the design of the main experiments, in which 32 scenarios of construction hazards related directly to the building's design.

Designer-builder design safety reviews in a CAVE

The video/audio recordings of the 10 conversations in the virtual site were analysed to determine the participants' responses to each of the 32 hazards presented. Three hazards were not clear in one or more of the recordings, so that the experiment yielded a dataset comprised of 290 responses (10 for each of 29 scenarios). The responses were analysed to determine designers':

(a) attitudes to the nature of the hazards and the degree of risk associated with each of them;
(b) recommendations for the actions to be taken; and
(c) perceptions of their responsibility for construction safety and their ability to influence it.

In 47% of the designers' responses, risk situations were identified as hazardous for the worker. A further 33% were considered to be potentially hazardous, and 20% were not thought to be hazardous at all. Of the hazardous or potentially hazardous situations, 61% were referred to as situations that are not dangerous provided appropriate safety means are implemented, while the remainder were viewed as inherently dangerous, irrespective of preventive measures.

Table 4 classifies the participants' recommendations for the actions that should be taken to reduce the risk of hazards. In 54% of the cases, they recommended that designs should be changed (items 4 and 5). For 29% (items 2 and 3) they recommended methods to improve safety that did not involve any change to the design.

Designer types were identified also with the objective of identifying their methods of operation and the impact of the dialogue on the participants' attitude to risks was analysed.

Classifying the designers' responses according to the 'recommended way of handling' led to three subcategories of responses, as follows:

- The designer is not familiar with the safety problem, does not understand it, or does not recognize the designer's responsibility for the problem (responses 1 and 6 in Table 4).
- The designer understands or is familiar with the safety problem, but is not willing to change the design to enhance safety (responses 2 and 3 in Table 4).
- The designer understands or is familiar with the safety problem, and is willing to change the design in order to solve it (responses 4 and 5 in Table 4).

The scenarios and the results were also grouped according to the design stage at which decisions are made and according to the design subject. The design stages were: (1) schematic design; (2) design development (space partitioning and location of building systems); and (3) detailed design in preparation for construction (including fabrication detailing). The design subjects were:

(A) Construction details
(B) Details of building systems
(C) Allocation of space functions
(D) Structural details (rebar and steel connections)
(E) Façade appearance and site layout

Table 4 Participants' recommendations for handling design-related hazards

Recommended method	Responses (n = 290) (%)
1. No action necessary	11
2. The issue is not my area of responsibility; it should be considered by another designer	9
3. My design considerations supersede concern for safety, so protective measures must suffice	20
4. The design should be changed for safety reasons, to minimize the risk	24
5. The design should be changed for other reasons (maintenance, aesthetics) as well as for safety reasons	30
6. The issue is the contractor's responsibility; I would not dictate any other solution	5

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Table 5 Designers' recommendations grouped by design stage

Recommended method	Design stage		
	Schematic (%)	Detailed (%)	Construction (%)
1. No action necessary	13	10	14
2. The issue is not my area of responsibility; it should be considered by another designer	6	9	7
3. My design considerations supersede concern for safety, so protective measures must suffice	38	28	17
4. The design should be changed for safety reasons, to minimize the risk	25	30	21
5. The design should be changed for other reasons (maintenance, aesthetics) as well as for safety reasons	19	18	29
6. The issue is the contractor's responsibility; I would not dictate any other solution	0	4	11

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Recommendations at different design stages: The risk situations were classified according to the design stage during which decisions are made about them. The objective of this classification is to determine when in the design process designers think it is most possible to affect the design products. Table 5 presents the results by design stage.

Recommendations according to design subject: The objective of this classification was to determine the aspects of the design in which designers are flexible and open to changes, and the aspects in which objection to design changes will be elicited. The results presented in Table 6 show that in all decisions pertaining to the appearance of the structure (column E), designers felt that their design statement overrides any safety consideration (46% responded that their design consideration superseded safety concerns and that therefore the way to safeguard against accidents is to adopt protective measures). In matters that concern decisions pertaining to construction details, the designers exhibited flexibility to changes (A, B, D) and very high flexibility to changes was evident in design issues related to building systems details and to structural details (76% and 60%, respectively, replied that the design should be changed for various reasons).

Internal reliability of the experimental method: Eight of the 10 designers who participated in the experiment completed a post-experiment questionnaire in which they were asked to rank different

Table 6 Designers' recommendations grouped by design subject

Recommended method of handling	Design subject				
	Detailed construction details A(%)	Building systems details B(%)	Division of service areas C(%)	Structural details (rebar and steel connections) D(%)	Appearance & function of façade and entrance areas E(%)
1. No action necessary	17	7	8	10	13
2. The issue is not my area of responsibility; it should be considered by another designer	6	7	4	5	13
3. My design considerations supersede concern for safety, so protective measures must suffice	17	7	33	10	46
4. The design should be changed for safety reasons, to minimize the risk	22	50	21	40	13
5. The design should be changed for other reasons (maintenance, aesthetics) as well as for safety reasons	24	26	33	20	13
6. The issue is the contractor's responsibility; I would not dictate any other solution	15	2	0	15	2

Table 7 Results of the post-experiment questionnaire

Question	Average	St. dev.
1. Were the hazards facing the construction workers clear to you?	4.1	1.4
2. To what extent did you feel that the scenarios represent real construction site situations?	4.0	0.8
3. How strongly are the hazards in the situations displayed related to the designer's decisions?	2.9	0.6
4. How good was the visual display?	3.6	0.7
5. How reliably did the scenarios represent the real world?	4.0	0.5
6. How important is the architect's attitude to site safety?	3.5	1.1
7. How important is the structural engineer's attitude to site safety?	3.6	1.1
8. Was the construction method clear to you in every situation?	4.3	0.9

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items regarding the reliability of the experimental tool and the user's experience on a five-point scale (1 = Not at all, 5 = Very much). The results, listed in Table 7, show that the virtual site communicated the issues clearly (items 2, 5 and 8 in the table).

In many of the transcripts, one can clearly discern development of the designer's perception of the hazard and of their attitude to possible design changes as a result of the dialogue with the researcher fulfilling the role of the builder. Figure 4 presents three examples of such development of thinking. The designers attest to themselves as lacking knowledge on certain safety issues and reveal that some of the considerations are absent from their day-to-day design decision-making system. Openness to design changes is expressed in situations in which such changes are expected to have no effect on the appearance of the building; however, when appearance is affected (Example 3), design considerations supersede safety considerations.

Discussion

Value of the dialogue and visualization

The first question posed asked whether a dialogue with construction professionals, conducted while touring a virtual construction site, can improve designers' awareness of and sensitivity to hazards. The answer is generally positive. Analysis of results obtained from the main set of tests indicated that in 45% of the cases (14 of 31), potential to enhance safety was identified. Emphasis may be placed, however, on two design subjects in which the possible effect is strong and clear, namely building systems and structural details, though there is potential for improvement also in all that pertains to the architectural building details.

Many cases were found in which the designers were exposed for the first time to the building professional's safety considerations during the conversation and tour of the virtual construction site. In addition, the dialogues revealed several situations in which designers expressed openness to design changes to increase safety following explanations given by the building professional. This, however, should be taken 'with a grain of salt' and it must be mentioned that willingness to make design changes was usually manifested in changes in the internal division of service areas, in building details, in structural details, and in the detailed design of the building's systems. No willingness was expressed regarding changes that benefit safety in issues that relate to the schematic design or the buildings' façades.

There were also many situations in which subjects failed to identify a risk but after the guided tour claimed that design changes should be considered to improve safety. This attests to the benefit of the conversation with the building professional, which is manifested in two ways: identification of improvements in the said structure, and learning about construction safety considerations that can be manifested in the designers' future design tasks.

However, as we did not include a control group without the VR, we are not able to apportion benefit specifically to the VR technology. Despite this, we suppose that this value is greater than it would be from viewing drawings, because, as shown in Table 7, the design reviews enabled designers to gain a fuller understanding of the hazards, for example by making the construction method clear. This supposition is supported by the findings of Perlman *et al.* (2014) and of Chun *et al.* (2012, p. 40), who concluded that '… of the six potential hazards found with the assistance of the visualization technology, five would have been almost impossible to identify by conventional means'

In the experiments, the number of replications was not designed to constitute a representative sample and the value of the experiments was in the wealth of feedback that was to be obtained from the conversations, each of which lasted about an hour and a half. These interviews enabled a comprehensive, in-depth investigation of the issues using the virtual construction site as a visual mediating tool. Results of this stage are valuable in terms of their quality, not quantity.

Example 1: Installation of curtain wall structure (Hazard 7)

Builder: Installing this structure at such a height exposes the workers to a risk of falling. Are you, as a designer, aware of these risks? Do you have any influence over such a situation?

Designer: I understand what you're saying. I wouldn't have thought of that myself. Now that you ask, I would ask the engineer who's planning the welding how he intends it to be built. I receive drawings for inspection. I wouldn't have noticed that. I check the opening directions of the window, and that it can be opened, I check sealing.

Example 2: Exit door to roof (Hazard 14)

Builder: Here we see a door that leads into a narrow passageway near the roof edge, while during construction there is only a temporary railing to protect the workers from falling. Do you, as an architect, have any influence over such a situation?

Designer: Now that you've shown me, I think I do. Before, I wouldn't have even thought of it. I'm starting to be impressed with what you have here. It's eye-opening. Designers don't have this knowledge.

Builder: The hazards are based on a study conducted in the US on the impact of design on safety. It included 400 different design items. We chose what we considered to be the most essential.

Designer: Now that you've shown me - yes, I think it should be changed. Before, I wouldn't have even thought of it. I didn't want to, let the contractor beat his brains out.

Example 3: Light railing (Hazard 32)

Builder: We can see one building with parapets that are built as early as the structural stage and opposite it is a building for which light railings were designed. This creates a situation whereby during construction the temporary railings are not satisfactory and the workers are exposed to the risks of working at a height.

Designer: This is very convincing for designers. Foremen are familiar with it on a daily basis. I have construction experience, the safety issue should affect the design. Not on a safety/access consultant level but rather the designer should be familiar with the safety issue. Why should I need a consultant to tell me how to design passageways for invalids? The architect should know it. It should all be part of the designers' thinking.

Builder: Let's go back to our specific case.

Designer: From an architectural perspective, a built parapet is not nice, I would tend toward the architectural consideration. I'm not a safety engineer. Architecture is always the first consideration. I'm willing to give in on issues that don't make a difference to the architectural design of the project, say the location of an air-conditioning unit - I don't care where it is, so let's look for a safe location. I have learned something.

Figure 4 Examples from transcripts showing the impact of the designer–builder conversations

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Designers' attitudes, awareness and understanding

The second and third questions posed in this work asked 'Can the risk inherent in a construction project be minimized by enhancing designers' awareness and understanding of safety issues? To what extent are designers willing to change design in order to enhance safety?' These questions relate to designers' skills and attitudes in relation to construction safety, and the potential mutability of their skills and attitudes.

Within this context the 'hierarchy of control' (Manuele, 2003) is a useful structure for evaluating the effectiveness of the actions that designers are willing to apply in different situations. Recommended methods 3 and 4 in Table 4 respectively reflect rejection and acceptance of the notion of elimination of hazards through design (the preferred approach in the hierarchy) or substitution with safer alternatives (the second level in the hierarchy). Method 6 reflects the designers' opinion that the contractors need to adopt one of the lower levels. Interestingly, the designers rejected the elimination and/or substitution approach far more in the schematic design phase than in the detailed design and construction detailing phases, as can be seen clearly in the results for recommended method 3 in Table 5. Their rejection of the higher two levels in the hierarchy is even more emphatic for issues that relate to the appearance and function of façade and entrance areas (Table 6). For the main study subject group (architects and structural engineers in Israel), this appears to confirm the assumption stated in the introduction that building designers typically differentiate user safety from construction safety, seeing themselves as responsible for the former absolved of responsibility for the latter.

Four types of designers, with distinctly different risk perception or identification ability and different approaches to design changes, can be distinguished. The classifications are defined as follows:

- Ability to identify hazards:
  (a) 'Do not identify hazards': Designers that the data analysis revealed did not identify or only partially identified ('No' or 'Partially') the situation as a safety hazard for workers.
  (b) 'Identify hazards': Designers that the data analysis revealed did identify ('Yes') the situation as a safety hazard for workers.
- Attitude to design changes:
  (c) 'Reject change': Designers who indicated options 2 or 3 as their recommended method of handling risks.
  (d) 'Accept change': Designers who indicated options 4 or 5 as their recommended method of handling risks.

Table 8 provides the distribution of the participant group sample from the third set of experiments in each classification. The fact that the largest group (50%) are those who lack skills but are open to changing their designs to improve safety, suggests that there is significant reason to expect that industry-wide efforts to educate and engage designers can bear fruit.

More detailed analysis of the Type 3 designers' responses indicates two approaches to decision-making with regard to the trigger to consider design change. All of these designers do not initially identify a given situation as a hazard to workers but the conversation with the researcher leads them to understand the impact of design decisions. Some of them rethink the situations and concur that design changes are in order only as a result of the conversation. Examples of the effect of the dialogue on these participants' attitude to risks can be seen in Figure 4. Other designers, however, draw motivation to change the design not from the conversation with the researcher but rather from a strong personal agenda that finds expression immediately once the hazard is pointed out and understood. For instance, one designer responded in many risk situations that 'It's a matter of systemic observation … there are many different considerations for such a situation …'.

An observation made across all of the experiments is that some of the designers consider certain situations in building construction to be 'inherently dangerous, irrespective of preventive measures', i.e. there are some situations that neither design changes nor the use of protective procedures or equipment can render safe. This reflects of course their perception of what degree of safety is acceptable, implying that in their view the safety measures in these situations are imperfect or incomplete because they leave a significant residual risk.

Table 8 Designer types

Approachattitude	a. Do not identify hazards	b. Identify hazards
c. Reject change	Type 1 10%	Type 2 10%
d. Accept change	Type 3 50%	Type 4 30%

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Conclusions

This work shows that consultation and dialogue with an experienced construction professional are highly beneficial for designers to appreciate the implications of designs for safety. The primary evidence for this is in the repeated observations of the participants, which reveals that various safety issues only became clear to them through the dialogue and demonstration in the VR. Figure 4 displays some of this evidence: in response to a question about whether the designer has influence, the designer states: 'Now that you've shown me. I think I do' (Figure 4). This evidence is suggestive of the efficacy of design reviews in VR for construction safety performed by designers in collaboration with construction professionals.

The results also show that such consultations can lead to specific design changes that enhance worker safety during construction. Yet designers are more willing to adapt design details than to change aspects that have an impact on the aesthetics of their designs. The research thus provides new understanding of designers' knowledge of and attitudes to construction safety hazards. While visualization of rich models provides opportunities to facilitate innovative collaboration between designers and contractors at different moments and through different media, the majority of opportunities for design changes are concentrated in just two specific areas of design: architectural construction details and detailed design of the various building systems. The participating architects were unwilling to contemplate making design changes to façades or aesthetic aspects of building designs.

Use of the VR tools enables in-depth exploration of the attitudes and behaviour of each subject, but it also limits the number of subjects that can be tested, which in turn limits the degree to which the results can be assumed to reflect designers at large. The major advantage of the CAVE is that one can situate the subjects in unsafe conditions, exposing them to hazards for the sake of experimentation, without any real danger; this could not be done ethically in a real construction site. The experiments also revealed the advantage of the CAVE over construction drawings: designers gain a fuller understanding of hazards than they do from drawings, and contractors can mobilize their experiential knowledge of the site in the VR context.

Two technical limitations of the VR research method should also be mentioned. First, in the pilot tests the complexity of the digital model and the technical difficulties encountered when transferring the model from the building information modelling (BIM) system to the CAVE system restricted the level of realism that could be displayed in the models. This was largely corrected for the main study, but preparing the model required an especially large effort. Secondly, transcription of the experiments from the audio and video recordings, as well as interpretation of the transcriptions, required a great deal of work and the interpretation is subjective by nature. Clear classification of the participants' responses to each situation, which was verified by two other members of the research team, was designed to minimize the effect of the interpretation's subjectivity.

The experiments also provided qualitative evidence of phenomena that require more focused research. In many specific situations where changes to aesthetics might have reduced exposure to hazards during construction, designers overall expressed the view that the workers and contractors were themselves responsible for their safety, and that if only they would abide by all the regulations, it would be possible to build any design without accidents. This attitude favours mitigation (by using personal protective equipment, using temporary railings, following standard procedures, etc.) over changing design to eliminate hazards.

This appears to be grounded not only in designers' lack of appropriate and sufficient knowledge to allow them to correctly influence construction safety, but also in their attitude toward and understanding of construction. Most of the designer participants appeared to be insensitive to the aspect of exposure over time of workers to safety hazards. They appear to be familiar with the notion of exposure in space, such as exposure to falling hazards, but they are not sensitive to the notion of exposure in time: none expressed any concept of the length of time during which a worker might be exposed to work at height as a hazard, with or without personal protective equipment, nor to the value that might be obtained by simply reducing the duration over which workers were exposed to hazards. They appear to think of buildings primarily in their final form, as static products, and not as the results of dynamic processes that must themselves be designed.

Differences in attitude to responsibility and liability were also revealed. The basic attitude of Israeli designers, where, as in the US, responsibility for safety is borne solely by the builder, is to avoid responsibility for safety as far as possible. Their perception of the legal liability is that it is desirable to avoid taking any action at all toward safety, lest their actions be perceived as making them responsible or culpable in any way if an accident should occur. This behaviour leads to a state of affairs in which construction safety is not considered and cannot influence the building design. The attitude of UK designers, on the other hand, generally embraced the idea that construction safety was a joint responsibility, and that while the expertise

lay with the builders, designers were not exempt from considering safety. This may be a result of the regulations that assign collective responsibility and liability for safety.

Future research that compares the different jurisdictions and their respective legislation and codes, as well as their resultant effects on safety culture, practice and performance, might better guide policy formulation. Aspects that should be considered include:

- Collective responsibility, including designers.
- Leadership of the safety issues in projects by a professional in the role of the 'design and construction coordinator' appointed by the owner, as in the existing UK model.
- Performance-based regulation rather than prescriptive regulation.
- Mandated preparation of a construction safety plan through collaborative work of the design team with construction advisors who should be drawn from the project's contractors whenever possible.
- Mandated requirements for designers to obtain formal training or instruction on construction safety as part of their professional training and in the initial years of their professional work experience.

These measures hold the potential to significantly improve the knowledge and involvement of designers in safety issues in particular, and construction in general, without detracting from the builders' responsibility for safety during construction. The intention is not only to introduce the safety issue into the project's early design stages, but to recognize the considerable effect that designers have during construction itself, when frequent design changes undermine the builder's ability to properly plan construction activities. These measures may reduce workers' exposure to hazardous situations during construction.

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Note

1. 'CDM coordinators' as defined by UK CDM regulations (CDM, 2007).

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