INTEGRATION OF CONSTRUCTION SAFETY IN DESIGN AND CONSTRUCTION EDUCATION THROUGH THE USE OF BIM

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ABSTRACT

The U.S. construction industry has incurred the most fatalities of any industry in the private sector in recent years. It is partly due to the fact that designers usually lack design for construction safety knowledge, resulting in many safety hazards manifesting themselves in various stages during the construction process. In this study, the researchers describe a designing for construction safety tool which makes designing for construction safety suggestions available to designers and constructors in an efficient way. The researchers also recognized the innate value that this software tool can have in an academic setting. Using this designing for construction safety tool and different models showing the construction process of a building at various stages of completion, students can learn to identify hazards that may arise during the construction process and this will increase their awareness of construction safety at both the design and construction stages of a project .

Keywords
Construction Safety Training, Model Checking Software, BIM, Designing for Safety, 4-D-Safety

1. INTRODUCTION

The U.S. construction industry has historically incurred the most worker fatalities of any industry in the private sector. While many reasons for this statistic may be postulated, it is partly because designers do not have exposure to design for construction safety knowledge, which results in many hazards being designed into in the project models/drawings. Gambatese (2003), through a survey of 36 U.S. civil engineering departments, found that none offered a course entirely devoted to construction safety. To improve the current situation, one potential solution would be to provide architecture and other design students with formal training on the federal Occupational Safety and Health Administration (OSHA) standards. For example, it would be helpful if designers were required to take a 10-hour OSHA class. The second potential solution would be to provide designers with software tools which could provide safety suggestions that could be incorporated during the design review process. The researchers in this study adopted the second solution and integrated the designing for worker safety software tool with Building Information Modeling (BIM) technology. The designing for construction safety tool was developed to automatically check BIM and make the designing for construction worker safety suggestions available to designers and constructors in real time.

The researchers also recognized the innate value that this software tool can have in an academic setting. Using this designing for construction safety tool and different models showing the construction process

of a building at various stages of completion, students can learn to identify hazards that may arise during the construction process and this will increase their awareness of construction safety at both the design and construction stages of a project .

2. DESCRIPTION OF THE DESIGNING FOR CONSTRUCTION SAFETY TOOL

2.1 Background

The designing for Construction Safety Tool was developed based on previous studies (Gambatese et a1997) which had already developed and compiled numerous designing for safety suggestions. These past research studies found that fall accidents account for a large portion of construction injuries and fatalities. In this study, the construction safety checking system was mainly targeted at eliminating potential fall hazards. The designing for construction safety best practices were reviewed to identify those provisions that deal with the fall protection. Currently more than thirty provisions which are related to the fall protection have been isolated. These suggestions were classified into two categories. The first category of suggestions are constrained either by precise parameters or by certain materials, such as "Design window sills to be 42 inches minimum above the floor level. Window sills at this height will act as guardrails during construction." Another kind of suggestion is currently uncheckable. A concept can be uncheckable because BIM may never have the information, or because the information will exist only on site in the actual building, or in the mind of an inspector. For example, one best practice is "Design appropriate and permanent fall protection systems for roofs to be used for construction and maintenance purposes. Consider permanent anchorage points, lifeline attachments, and/or holes in perimeter for guardrail attachment." OSHA standards (2009) also correspondingly require (Appendix C to Subpart M fall protection):

> "(h) 'Tie-off considerations.' (1) One of the most important aspects of personal fall protection systems is fully planning the system before it is put into use. Probably the most overlooked component is planning for suitable anchorage points. Such planning should ideally be done before the structure or building is constructed so that anchorage points can be incorporated during construction for use later for window cleaning or other building maintenance. If properly planned, these anchorage points may be used during construction, as well as afterwards."

After the designing for construction safety suggestions were classified, two major components of the Model Checking System needed to be developed: the Main Dictionary and the Constraint Model.

2.2 System Architecture

After the collected suggestions were formalized, the next step was to develop the proposed Construction Safety Checking System. The purpose of this system is to automatically check imported drawings which are in IFC format to alert designers of opportunities for improving construction safety. The system is developed to provide design for safety knowledge quickly, easily and economically.

Figure 1 shows the architecture of the Construction Safety Checking tool. The x-axis represents the project process from the beginning of the design to delivering the documents to constructors. This begins on the left with the design development period when the designers draft the initial drawings. It then evolves into the design review phase and the agency permitting phase. This culminates in the construction period. The design process is an iterative one. Users can submit construction documents and check the design for non-compliance by using the Construction Safety Checking software tool.

After the report identifies the problematic building components, the designer(s) can revise their drawings by returning to the architectural design tools. The core of the entire process is the model checking software which is supported by the Main Dictionary and a design for construction safety rule set. After the design for construction safety knowledge has been incorporated into the construction documents, shop drawing can be delivered to constructors for further construction work.

The Construction Safety Checking software tool is based on a Model Checking Software. An online version of the Solibri software application or the AEC3 XABIO web-based test-bed can be adopted as the model checking application. AEC3 XABIO uses EPM and Octaga technology (Nisbet 2009). AEC3 XABIO can check an entire regulation or an individual clause and then generate a full explanation. It is web-based: the Apache Tomcat web server is used to harness the EXPRESS Data Manager database, and the Octaga 3D viewer is used to highlight the building elements at issue (AEC3 2009). This application is designed to find potential problems, physical conflicts, or design code violations in a building model.

Two additional important components of the Construction Safety Checking tool are the Constraint Model and the Main Dictionary. After the designing for construction safety suggestions were classified, a MS Excel spreadsheet is used to collect 'terms' and 'properties' of these suggestions. It is helpful to avoid having the concepts expanding in an uncontrolled fashion. Lastly, the Main Dictionary was developed, which is comprised of terms, objects, and properties critical for communication between the Model Checking Software, BIM authoring tools and the Constraint Model. Note that the same property can occur within the safety suggestions in many places. The Main Dictionary can make sure that the property is always assigned the same meaning and unit of measurement.

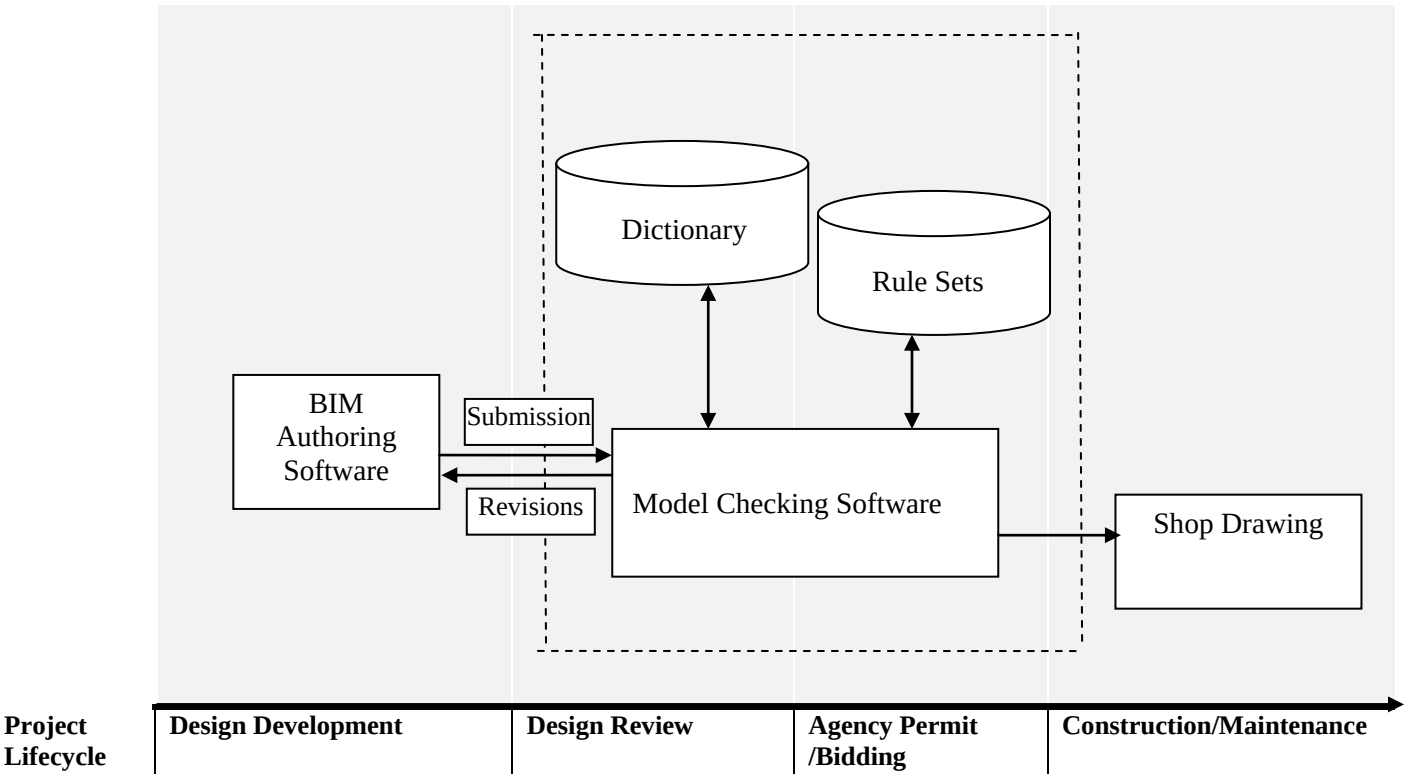

Figure 1: Architecture of Construction Safety Checking Software tool

The constraint model, also known as rule sets, is the electronic format design for safety suggestions. It takes three steps to transfer the original paper-based design for safety suggestions to the Constraint Model. The first step is to transfer the original design for construction safety suggestions into computer readable baseline electronic suggestions which are in XML format. Then the logic is established between different 'terms' and 'term properties' in each suggestion by tagging them and assigning different colors to the tags based on their classification. Finally, different logic is encoded, which makes the baseline electronic suggestion transfer into Safety Constraint Model/ Safety Rule Sets.

2.3 Tool Functionality

After the architecture of the tool had been determined, the next issue was to define the functionalities of the tool. The safety checking system was designed to have two main functions. One function consists of checking the drawings against the design for construction safety rule set. The tool should also be able to provide safety information related to certain building components. This is based on both the characteristics of the design for construction safety knowledge and the reasoning process of the safety checking tool. One of the differences between building codes and design for construction safety knowledge is that a large number of design suggestions are in the textual form without any parametric information. Many of these suggestions are very difficult to encode into rule sets that can be compared with the properties of building components and be used to restrict non-compliance. Consequently, it is better to keep them in their original form and show them to the user in text. In contrast, most building codes are connected to attributes that can be physically measured. Second, the building code checking systems are generally restricted to providing detailed information after the checking work has been finished. The design for safety tool is expected to provide suggestions during the design process. These two points are very similar to delivering constructability knowledge to designers during the preliminary design phase. By considering the above points, the research will need to find an appropriate way to deliver safety knowledge to designers.

The process of checking a construction drawing includes the following steps. First, the user loads the design into the rule checker. Then the 3D view can be shown on the right hand side of the safety checking tool. The navigation functions usually include Zoom, Spin and Walkthrough. On the left hand side are checkboxes which are used to select objects and rule sets. The user could get detailed properties of any object by selecting an object tab. The user also can access all design for construction safety suggestions by selecting them from the rule sets. A detailed explanation of every suggested design provision will be provided and some graphs will also be given to illustrate complex issues. Next, the user can select the rules that will be used to check against specific objects. After running the checking function, two sets of results will be produced. One is a list of all non-compliance issues identified in the drawings, along with suggestions about how to eliminate or mitigate these issues. The user could print the report in PDF or other forms. Another set of results will be shown on the right hand side in the form of a 3D view. Red circles will show all the components which violate certain rule sets. After getting the report from the model checker, the user can change drawings in the architectural modeling tools or keep the original design ideas if other requirements need to be met. Designers will be advised to keep a record of their decisions for future use.

2.3 Case Study on Using Safety Checking Tool

Next a case study of how to use the Safety Checking Tool to check a building model is discussed. The user wants to check if the pitch of a three story building with a sloped roof meets the safety requirement. The user imports the sample model into the Model Checking Software to check whether the roof slope

meets the requirement. Because according to OSHA standard, low-slope roof means a roof having a slope less than or equal to 4” in 12” (OSHA 2009), the following requirement need to be met. “Minimize the roof pitch to reduce the chance of workers slipping off the roof.”

After loading the Constraint Model and clicking the ‘Navigation’ button, the system would generate a 3D view of the building model. As shown in Figure 2, the roof of the subject building model is so sloped that there is a possibility that the roof does not meet the requirement. Then the pitch of the roof can be checked. After running the Model Checking Software, the tool will give the results as shown in Figure 3.

The detailed description demonstrates that the pitch of the subject roof does not meet requirements. The project participants need to consider either revising the building model or installing fall protection on the construction site. Suppose that after discussions among the Design-Build team members, the designers can go back to Revit Architecture to revise the building model. As shown in Figure 4, the Revit Architecture model shows the roof slope is 5”/12”, which causes serious construction site fall hazards, since past experience has verified that the roof pitch should be no more than 4”/12” to be a safe work place . The user should modify the parameter of the roof to a more reasonable number.

3. EDUCATIONAL USE

The Construction Safety Checking Tool and BIM offer a tremendous opportunity of learning for design students. The objective is to acquaint design students with examples of how they can impact construction worker safety in a positive way through their design decisions. Using the Construction Safety Checking Tool and BIM models representing a building at various stages of completion, a student can explore and visualize the safety hazards present at each stage of the construction process. This will enhance their ability to identify risks which is the first step in any risk mitigation process. For example, Figure 5 shows a three story building which has a stair at the second floor. During a certain period of construction process, there is a opening on the second floor which is a potential safety hazard to construction workers when the stair has not be been installed. A temporary barricade structure needs to

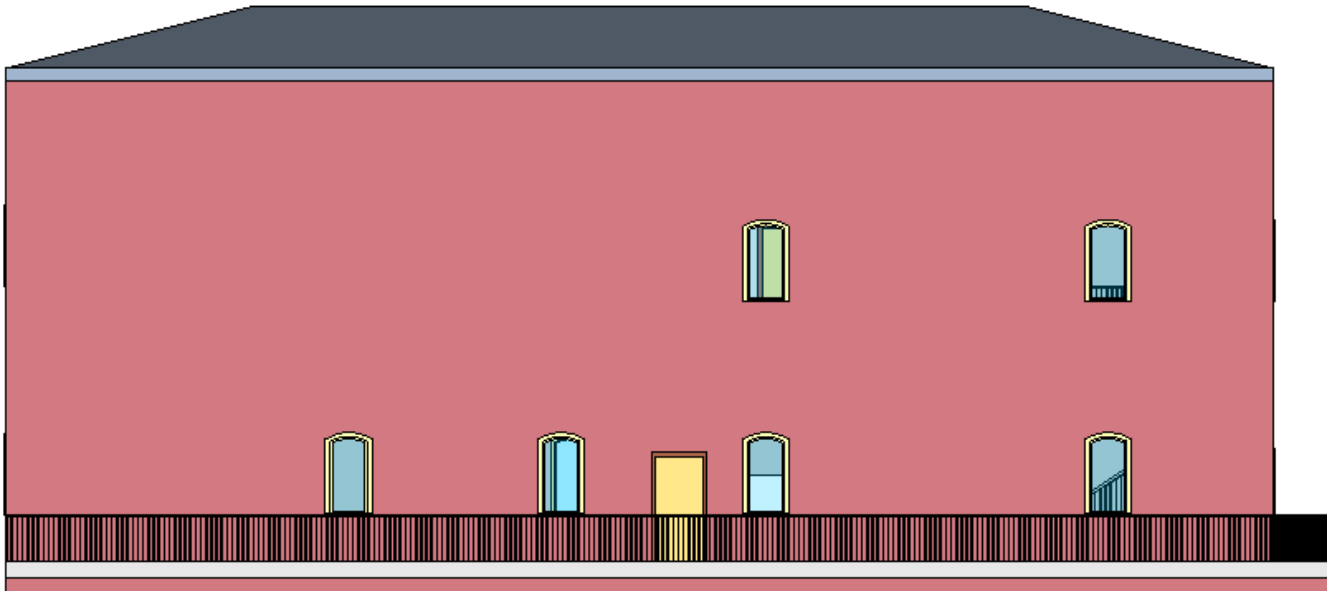

Figure 2: Slope of the Building Roof Evaluated Using the Model Checking Software Tool

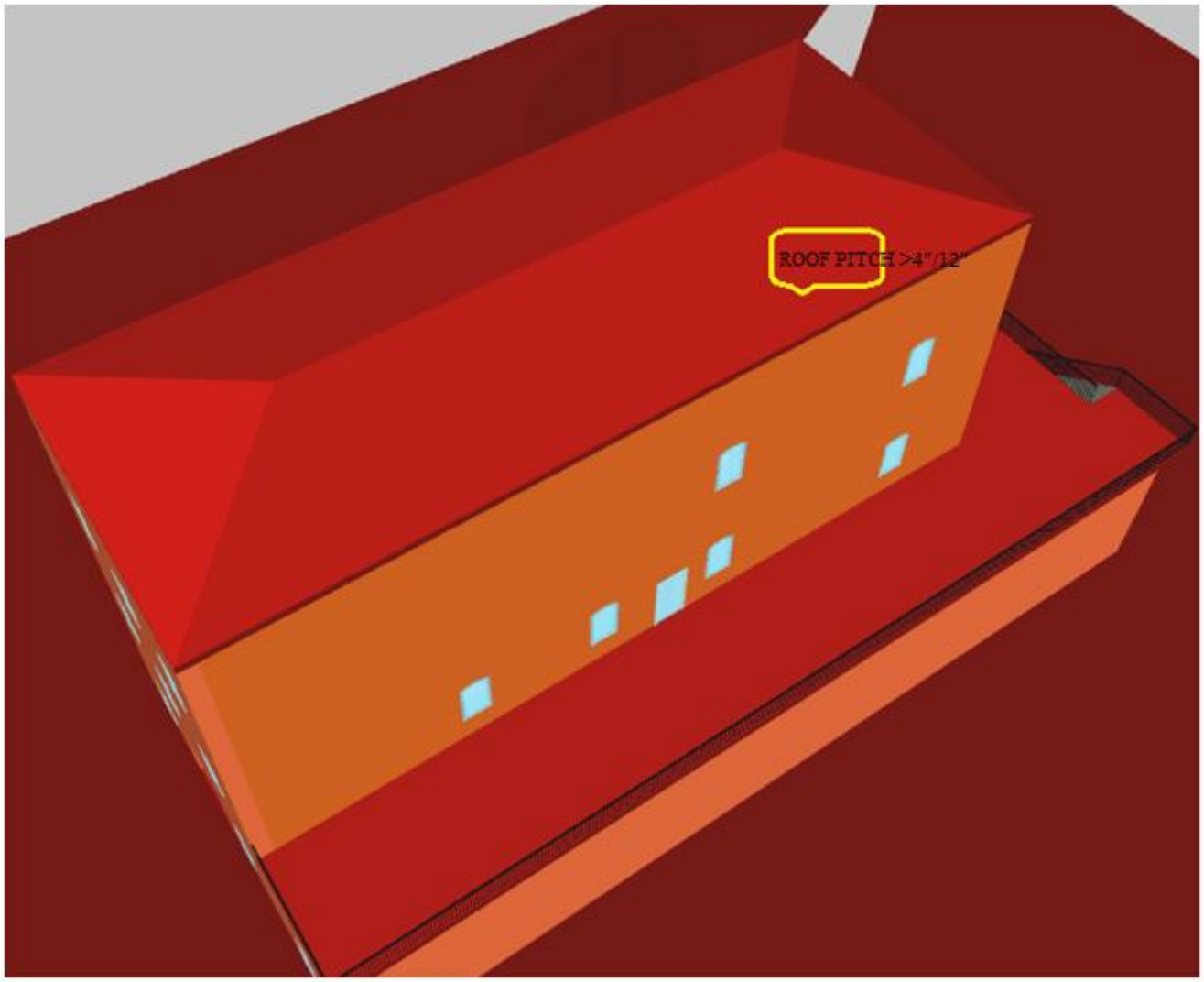

Figure 3: Non-Compliance in 3-D View

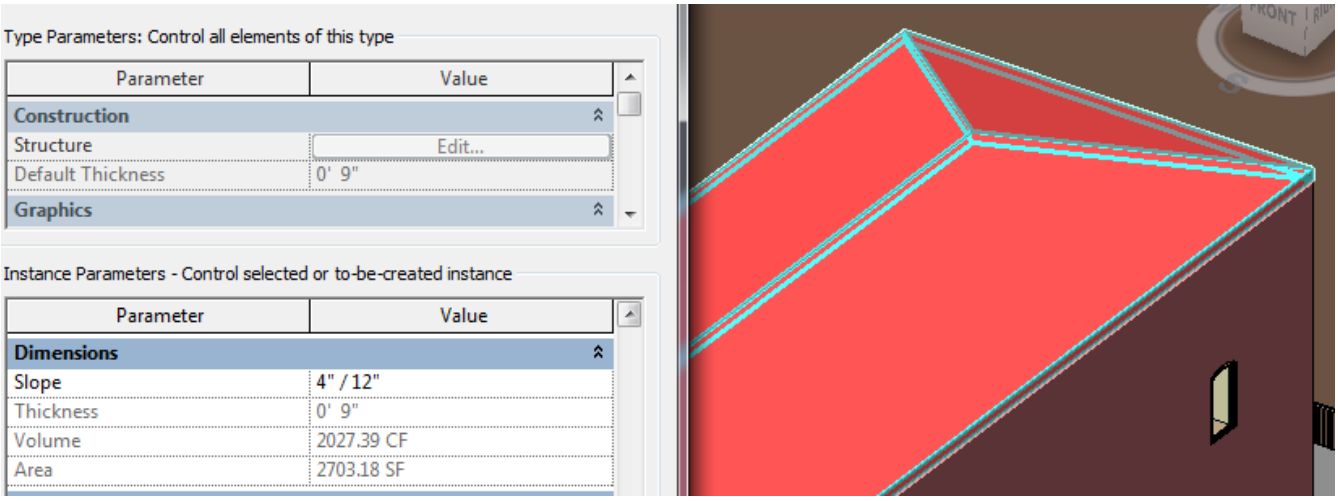

Figure 4: Change in Slope Parameter of the Roof

be set up to protect the construction workers. However, these safety hazards will disappear after the railings are built around the floor opening, so the model checking software cannot identify these kinds of hazards when the project is complete. To overcome this drawback, it is necessary to check the buiding model at specific points of time during the construction period. Figure 6 shows all the stairs and openings in the building detected by an IFC viewer. As shown in Figure 7, the students could use the model checking software to detect the opening on the second floor, which poses a severe safety hazard during the construction process.

The project schedule undoubtedly impacts construction site safety. For instance, construction workers tend to neglect surrounding hazards when an expedited schedule is assigned to their tasks, which causes disproportionate construction injuries and fatalities. In contrast, a well-organized project reduces the pressure on construction workers and correspondingly diminishes the occurrence of accidents. The BIM application enables "what-if" scenarios for visual risk management and time-based workflow planning when linked with Clash Detection. The “what if” analysis is a structured brainstorming method which usually is used to uncover hidden hazards. The 4D models link components in 3D CAD models with construction schedules. The 4D model allows project participants to view the planned construction of a facility over time and review the status of a project in the context of a 3D CAD model. In practice, many constructors have used 4D models to study different design and schedule alternatives and educate workers about what would be happening during each stage of construction. The same process is used to help students in becoming proficient in identifying safety hazards as the completion of a construction project progresses over time.

Although coordination between scheduling and safety planning has been identified as an important factor to a successful project, this issue has not been fully discussed in a 4-D environment. 3-D CAD technology is being substituted by BIM technology. With the rapid progress of BIM technology, it is necessary to propose the concept of four-dimension-safety (4-D-Safety). 4-D-Safety is the technology that uses 3-D software to detect the locations of the construction site hazards and meanwhile uses scheduling software to identify corresponding high-risk time periods. There are various construction hazards on construction sites during different construction time periods. Since the construction site conditions vary according to the progress of the building, the construction hazards that exist during the construction process of a building structure will disappear with the completion of that building structure. The corresponding protective measures must be taken for the appropriate situation and at the right time. This is another difference between design for construction worker safety suggestions and the building codes. Building codes are used to protect the public and end users who will take occupancy of the completed building. The Model Checking Software (MCS) just needs to check the as-build model to ensure that the building fulfills all the requirements. Design for construction worker safety protects the construction workers during the entire project life-cycle, i.e., the construction process is a major phase in which procedures should be taken to protect the safety of construction workers. The Model Checking Software (MCS) developed for this purpose is theoretically able to check safety conditions of a building information model at any point in time during the construction process. The project participants, only by coordinating the safety planning with scheduling in a 4-D environment, can locate potential construction site hazards in advance. By identifying hazards associated with a specific construction period, appropriate measures can be taken to reduce or eliminate the hazards during the design and construction process. This process of hazard identification and abatement during the construction process during both the design and construction phases is the basis for using this safety checking tool in an educational

setting to help students become more safety conscious during both the design and construction processes.

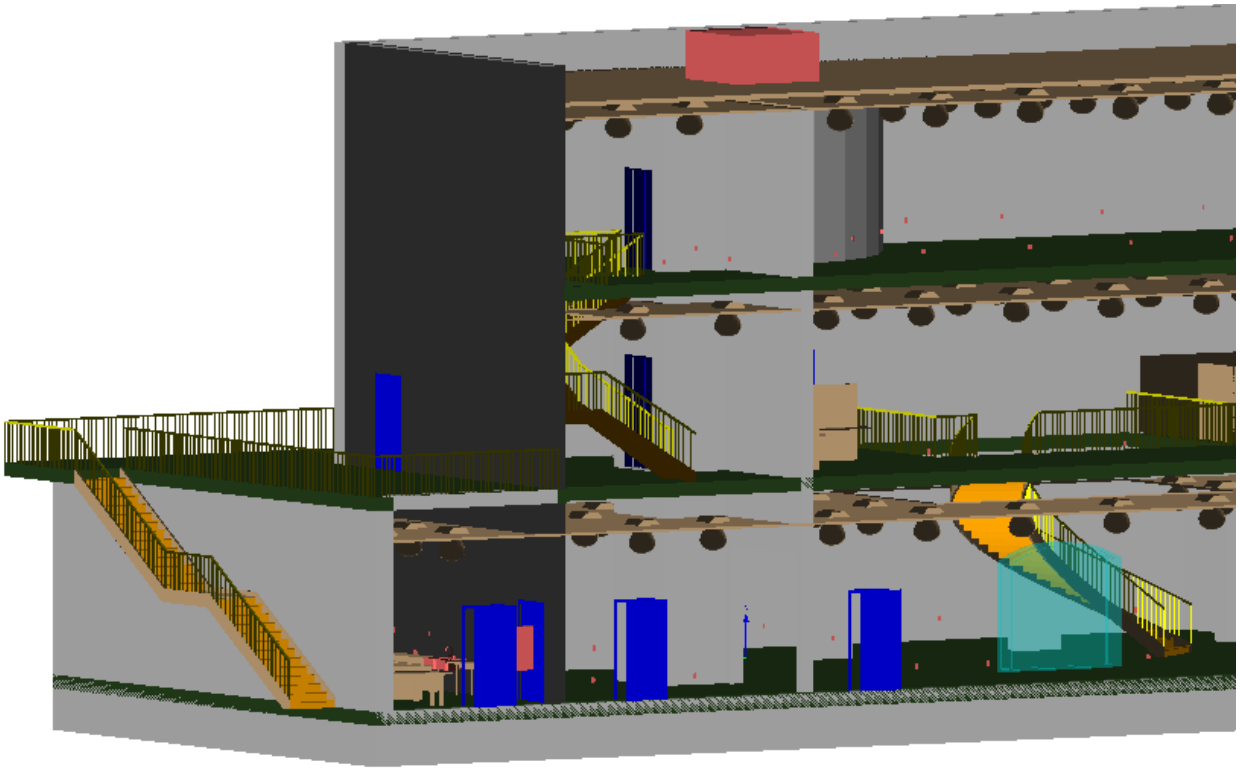

Figure 5: Section View of Completed Building Structure with no Safety Hazards

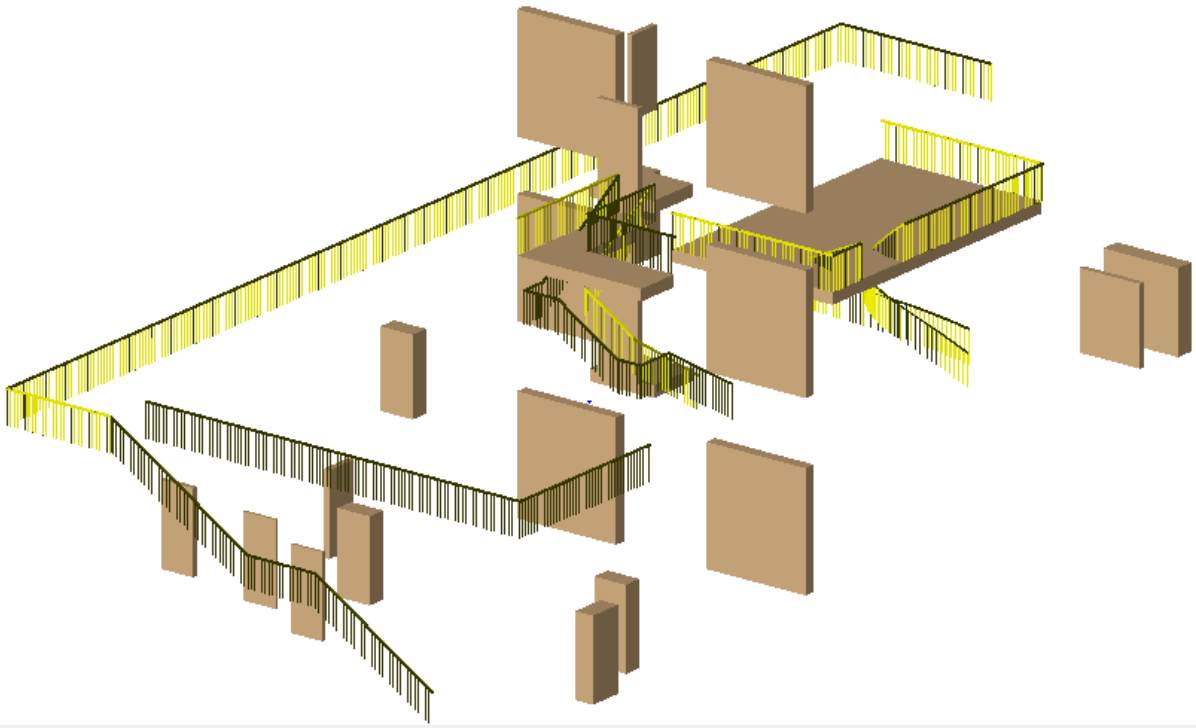

Figure 6: View of Completed Building Stairs and Openings

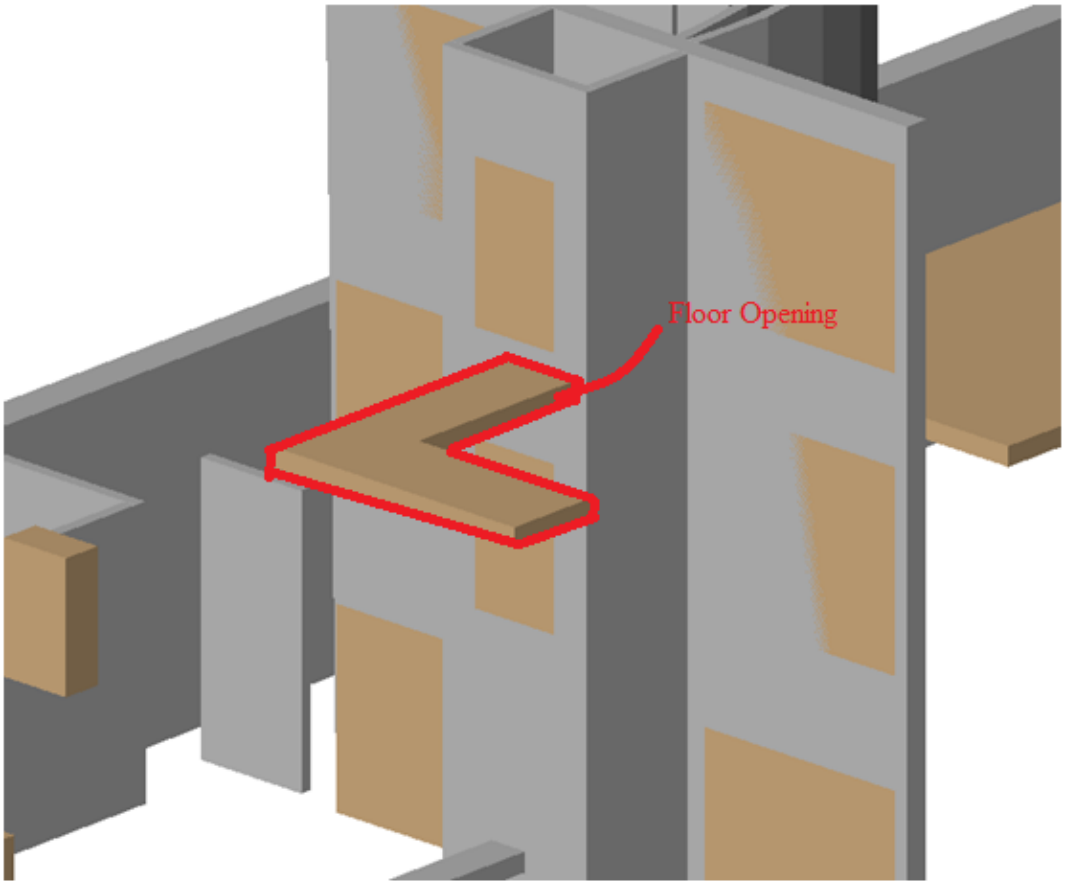

Figure 7: View of Floor Opening

4. SUMMARY

A design for construction worker safety software tool has been developed. This tool can automatically check for fall hazards in the building information models and provide design alternatives to users. It can be used by the architects/engineers during the design process or be used by the constructors before performing the construction work. The tool can also be used in educational settings to help students become more safety conscious by allowing them to check for safety hazards at any given point in time during the progress in the construction of a building.

This tool consists of a 'Model Checking Software' and the 'Constraint Model/Rule Sets'. The model checking software is an object-based rule engine such as Express Data Manager (EDM), which can conduct an automatic design checking process. These rule sets are based on electronic computer-readable construction safety suggestions. The user loads the subject building model into the design for construction safety tool. The user can get familiar with the building model through 3D navigation which includes functions such as zoom, spin and walkthrough. Then, the user needs to select the specific rules sets which will be used to check against the subject building model. After running the model checking

tool, two sets of results will be produced. One is a list of all non-compliances identified in the drawings, along with possible suggestions about how to eliminate or mitigate these hazards. Another set of results will be shown in the 3D view. The building model will be marked with colorful circles which highlight all the building objects violating certain design for construction safety rules. After getting the report from the model checker, the user can either change the drawings in the architecture software or keep the original design ideas if other requirements need to be met. The student can compare the list of safety hazards that they have identified to the list identified by the safety checking software tool and learn from the ones they missed. Future research will be dedicated to checking and validating the tool

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