Techniques for Building an OSHA Compliant Guardrail Structure

E. A. McKenzie, Jr., Ph.D., P.E. and Thomas G. Bobick, Ph.D., P.E., CSP

Abstract

In the construction industry, workers falling to a lower level has been the primary cause of fatalities according to the Bureau of Labor Statistics Census of Fatal Occupational Injuries database. From 2006 to 2010, an average of 353 construction workers died annually as a result of falling to a lower level. An average of 126 workers (36%) died when falling from unguarded roof edges, and through roof and floor holes or skylights. The National Institute for Occupational Safety and Health evaluated the strength of job-built guardrail structures around an opening. The study focused on a 2′ x 4′ opening typical of residential skylights. Nine full-time residential carpenters built guardrails for strength testing.

Guardrails were constructed with 2" x 4" lumber and 16-d duplex nails. The strength test determined if each guardrail could support a 200-lb loading on the top rail as required by the OSHA Fall Protection Standards (Subpart M). A quantitative pull test was then done to measure the strength and integrity of each guardrail. All nine guardrails passed the 200-lb drop test, and the strength test results ranged from 161 to 575 lbs. Three of the nine test subjects were randomly selected to construct similar guardrails using 3-inch all-purpose screws instead of nails. An average of 75 screws were used per guardrail compared to an average of 85 nails per guardrail. The strength of the structures built with screws was more consistent, and had a 67% increase in overall strength with respect to the nail structures and the strength test results ranged from 395 to 470 lbs. The overall strength and integrity of the structures was directly related to the construction techniques used by each subject. The successful construction techniques were determined to be the following: the orientation of vertical support posts relative to the applied loading, anchoring the vertical posts inside the opening, the overlapping of the rails of the structure, and the number, type, and orientation of the fasteners.

Introduction

Worker fatalities caused by falls

When working on steep-sloped roofs or near unguarded edges, openings, or stairs, employers are required to protect construction workers through the use of guardrail systems, covers, safety net systems, or personal fall arrest systems, according to OSHA regulations, 29 CFR 1926.500-503 (Subpart M – Fall Protection). Workers falling to a lower level has been the primary cause of fatalities in the construction industry since the Bureau of Labor Statistics started the Census of Fatal Occupational Injuries database in 1992. For the period 2006-2010, an average of 1,001 workers died each year in the construction industry. Of this total, an average of 353 (35%) died each year by falling from elevations. More specifically, 126 workers died each year when falling from unguarded roof edges, and through roof and floor holes and skylights. These are all work situations where workers could be prevented from falling by installing guardrails, either job-built or commercially available systems.

NIOSH study

The evaluation of the effectiveness and strength of a job-built guardrail versus a commercially available guardrail system was reported in Bobick and McKenzie (2005). This study was conducted by NIOSH engineers from the Division of Safety Research. It was limited in scope and focused on protecting a typical residential skylight opening (2′ x 4′). The nine test subjects were full-time residential carpenters. The subjects were asked to construct a guardrail structure around the perimeter of the opening that they thought would protect a person from falling into it, using construction-grade white pine 2″ x 4″ lumber and 16-d duplex nails. (The duplex nails were used to facilitate disassembling the structure after testing was completed.) All nine carpenters were informed that the top rail had to meet the OSHA specification (29 CFR 1926.502(b)(1)) that the "top edge height" had to be "42 inches…plus or minus 3 inches…above the walking/working level." The subjects were not aware of how the structure would be tested. The nine subjects constructed two job-built guardrails – one for a flat surface and one for a sloped (4/12) surface. This report focuses on the results related to the flat surface.

Drop testing for OSHA requirements

The job-built guardrail systems were evaluated to determine whether they complied with OSHA regulation 29 CFR 1926.502(b)(3). This regulation states that,

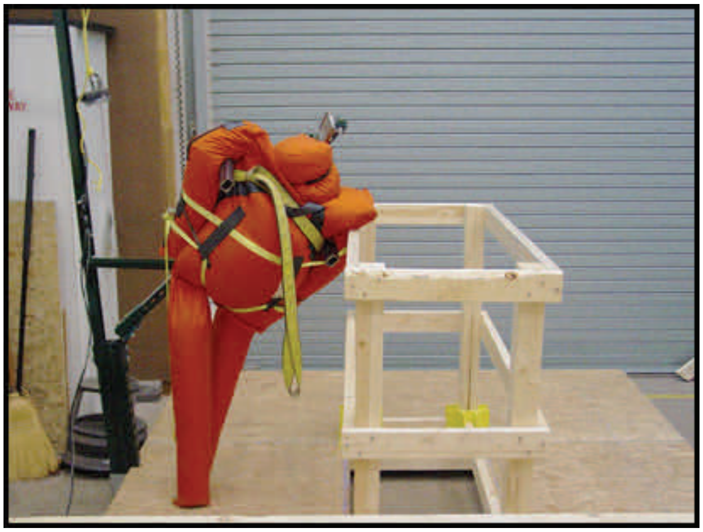

Figure 1. 200-lb Drop Test

"Guardrail systems shall be capable of withstanding, without failure, a force of at least 200 pounds (890 N) applied within 2 inches (5.1 cm) of the top edge, in any outward or downward direction at any point along the top edge." (Mancomm, 2012, p. 323) A testing system was developed to simulate the real-world scenario of a worker, weighing more than 200 lbs., tripping and falling into the top rail of the guardrail structure. A fire-rescue test manikin was mounted on a steel frame and was hinged at knee height to simulate the motion of a person when they trip and fall, as shown in Figure 1. Each drop of the manikin was calibrated to ensure that the applied force was always greater than 200 lbs. The test set-up and calibration procedure was described previously (Bobick *et al.*, 2010).

Pull-to-failure strength testing

The ultimate strength of each guardrail constructed was evaluated individually by using a NIOSH-developed pull-to-failure (PTF) test. The testing philosophy for this test was to quantitatively evaluate the ultimate strength of each guardrail configuration. The PTF test imposed a sustained force (lasting 2-3 seconds), which far exceeded the OSHA 200-lb falling test duration. A maximum pulling force of 800 lbs was generated using a 2-inch hydraulic cylinder, a battery-operated hydraulic pump, and a cable and pulley system as shown in Figure 2.

Figure 2. PTF Testing system

PTF and Drop Test results

Results from the testing of job-built guardrails built for the flat surface indicated that all of the structures passed the OSHA 200-lb loading requirement, as conducted in this research study. However, the pull-to-failure results ranged from 161 lbs to 575 lbs.

Visual analysis of the PTF results

The ability of a structure to withstand a single impulse, shock, or instantaneous loading (OSHA 200-lb drop test), does not correlate to its ability to withstand a sustained dynamic continuous load, such as found in the PTF testing. The linear frictional forces between the nails within the wood structure and the dynamic energy absorption

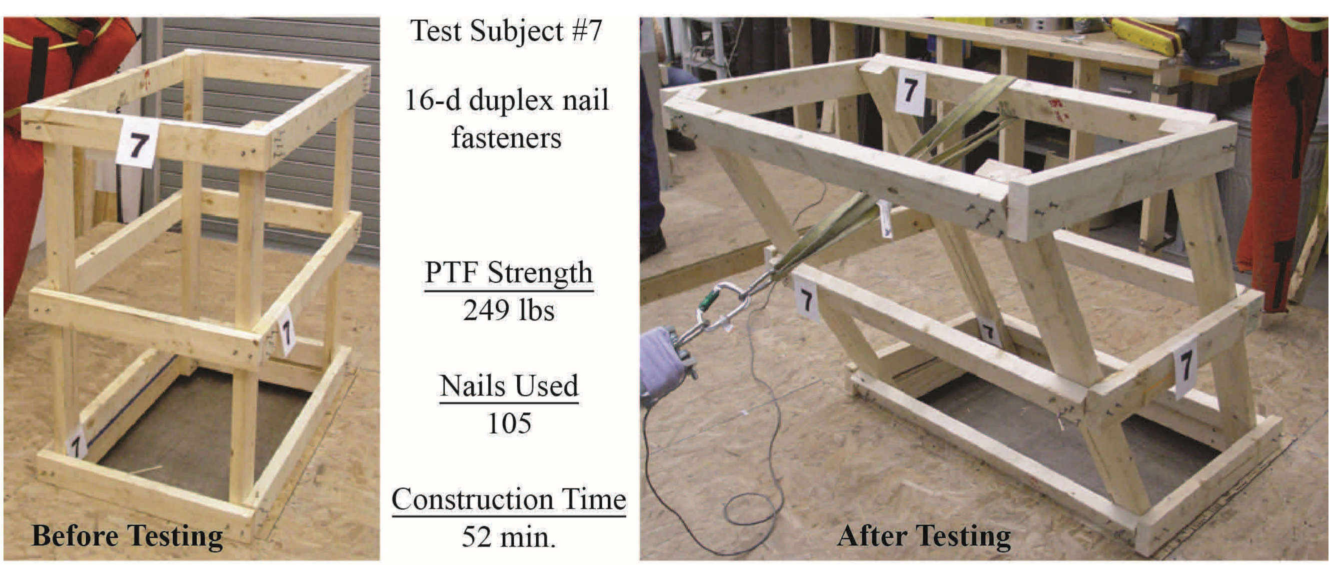

Figure 3. Subject #7 PTF Testing Results Using Nail Fasteners

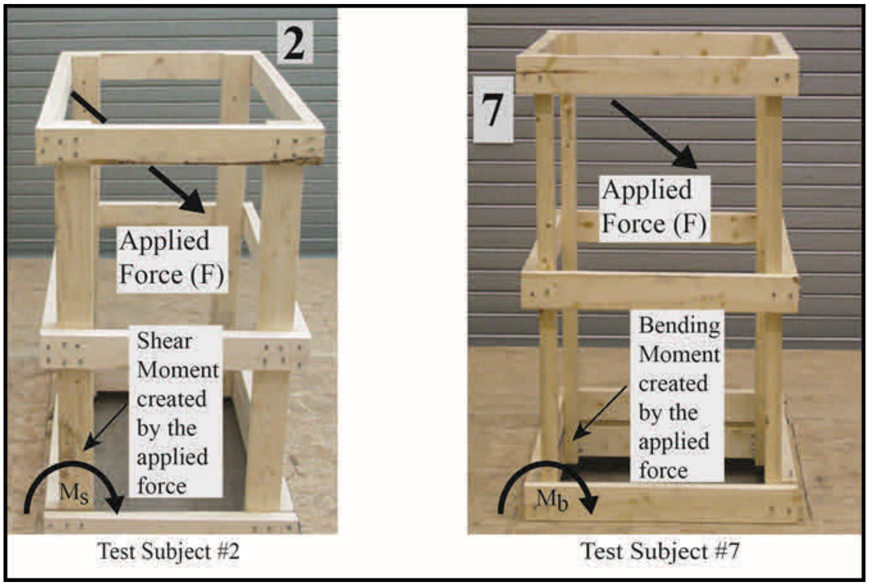

Figure 4. Shear Moment and Bending Moment Cases

(resilience) as a whole were substantial enough to resist a low impact, instantaneous 200-lb force. However, the sustained loading applied from the PTF test exceeded the linear frictional forces between the nail fasteners and the wood structure. Once the linear friction forces were exceeded, the structure began to move dynamically thus introducing a combination of bending and shear forces on the fasteners. The overall strength was then influenced by the construction techniques used. An example of the PTF test results and a before and after picture of the guardrail is shown below in Figure 3.

When guarding a hole or opening in a floor or flat roof, the direction of the worker falling (the applied loading) on the structure is not known, so an applied force in all directions should be considered. The applied loading (or force) will create a bending moment at the base attachment points. This will act like a giant crow bar and will either pull the fasteners out of the base or try to twist (or shear) the fasteners off the base. During the testing, one subject constructed the guardrail with the base fasteners being in shear during the evaluation testing (subject #2). That overall PTF strength was measured at 575 lbs. The others had the base fasteners in bending and the PTF strength range was 161-319 lbs. Examples of these two cases are shown in Figure 4.

Fastening the toeboard, midrail, and top rail to uprights was mostly constructed with overlapping segments. The number of fasteners used and the orientation of the boards varied. The predictability of how the midrails and top rails would react (splitting or not splitting) was dependent upon the fastener configuration. The lumber that the subjects used was construction-grade. An effort was made to select "clear lumber" for the 500 board feet of lumber used in the study. Despite being extra careful, some of the lumber had knots in them that contributed to premature failure during the pulling test. Some examples of how the wood split during the testing are shown in Figure 5.

The most critical factor identified to increase the overall strength and integrity of the guardrail structure was the construction practice of overlapping and fastening the toeboard, midrail, and top rail as shown in Figure 6. This is an example of a top rail that has been overlapped and fastened with two nails.

To emphasize the importance of overlapping the rails, the structure constructed by test subject number eight will be highlighted. The subject did not overlap the rails and had a respectable PTF strength of 249 pounds, but at the end of the test, the structure broke apart and introduced other safety concerns. It no longer provided adequate fall protection and had exposed nails and projecting cross pieces, as shown in Figure 7.

Guardrail system strength was not completely dependent on whether the boards split or did not split. Planning fastener patterns can help eliminate some of the splitting. The nail fasteners should be equally distributed into the board. When fastening into the short side of the 2" x 4", two fasteners should provide acceptable fastening strength. When fastening into the wide side of the 2" x 4", three fasteners in a triangle configuration should provide acceptable fastening strength . More than four fasteners in any one board was not a determining factor in the overall strength of the structure. Depending on the wood quality, sometimes five fasteners made the board crack before the loading was applied.

Additional testing using screw fasteners

At the conclusion of the initial study, the researchers wanted to evaluate and compare the strength of a similar job-built guardrail constructed with screw fasteners. For this additional testing, three of the original nine carpenters (subjects 1, 7 and 8) were randomly selected to return to complete the original task (as subjects 11, 12 and 13 respectively), except the fasteners were changed from 16-d duplex nails to 3-inch all-purpose Phillips head screws. Figure 8 provides the PTF test results and shows before and after photos of the guardrail. Table 1 indicates that

Figure 5. Examples of Wood Splitting

Figure 6. Overlap Mid and Top Rails

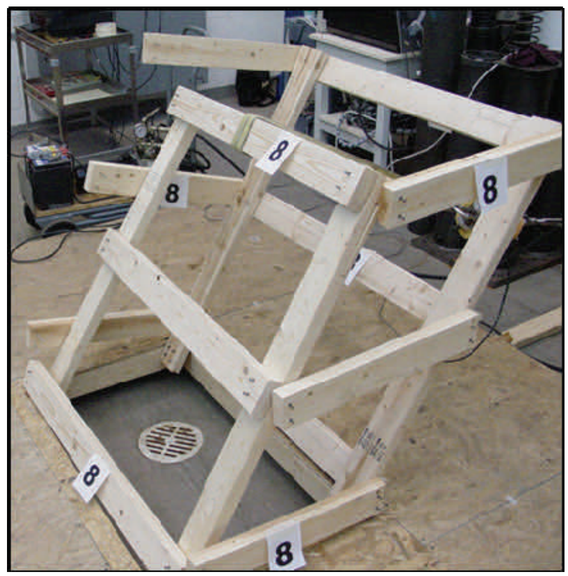

Figure 7. Subject 8: Structure after PTF Testing

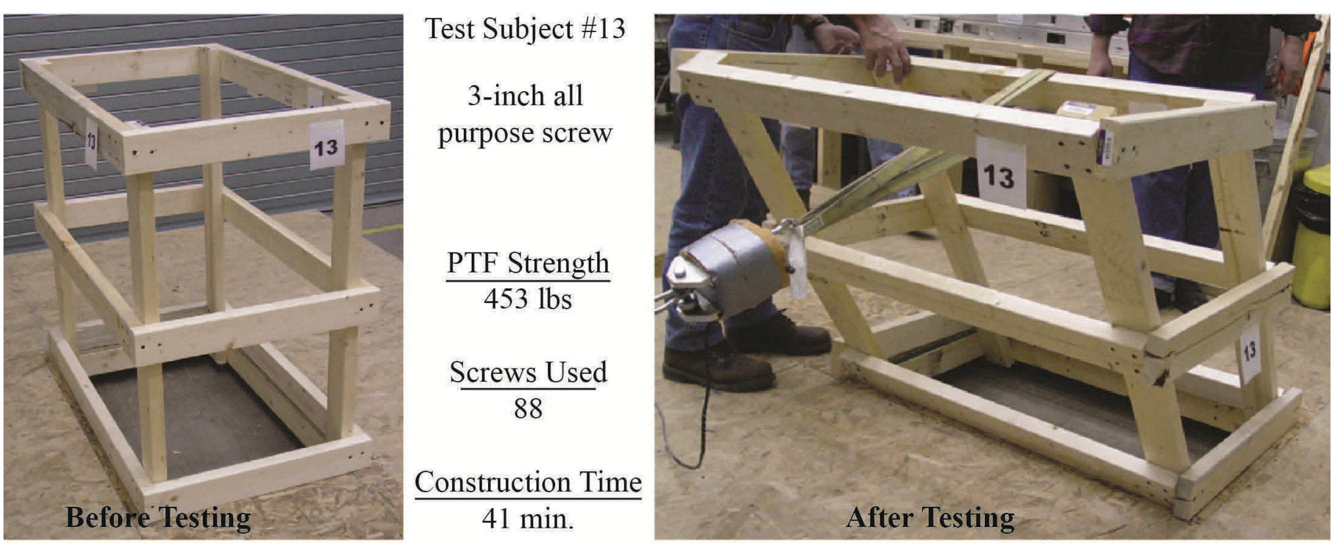

Figure 8. Subject #13 PTF Testing Results Using Screw Fasteners

Table 1. PTF Strength, Number of Fasteners, Construction Time

Test Subject Number		PTF Strength (pounds)		Number of Fasteners		Construction Time (min)	
Nails	Screws	Nails	Screws	Nails	Screws	Nails	Screws
1	11	260	470	82	78	25	22
7	13	249	453	105	88	52	41
8	12	280	395	64	60	24	20
Mean		263	439	84	75	34	28
Percent Change (Screws vs. Nails)		+67%		-10%		-18%	

the screw fasteners provided superior strength with fewer fasteners needed, and had reduced construction times. The benefits of using screw fasteners were discussed previously (Bobick *et al.*, 2010).

Discussion

Anchoring

Interestingly, what was initially thought to be a straight-forward task actually resulted in nine different designs. Some of the professional carpenters did not attach the vertical support posts to the inside of the opening, and instead attached the base of the guardrail structure to the roof surface. The job built guardrail structures attached to the surface had the lowest PTF test results. The carpenters who attached the vertical support posts to the interior surface of the hole used between three and five

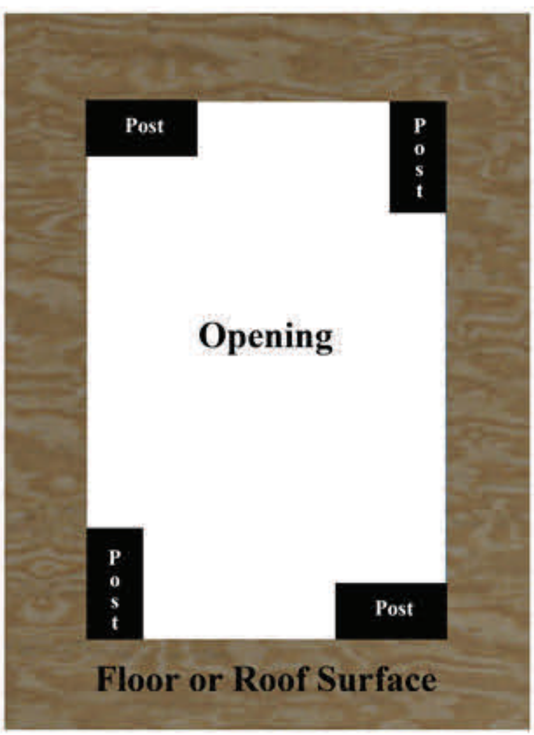

Figure 9. Top View with Turned Posts

16-d duplex nails. The testing showed that three or four nails gave acceptable fastening strength. Using five nails did not result in a measurably stronger structure. Subjects who used three nails spaced them out equally, which lessened their contribution to the splitting of the vertical post at the attachment point. The PTF testing evaluation was an extreme condition, which quantified the overall strength of the structure, and was not intended to represent a real-world event. When subjects constructed the midrails and top rails, there was a lack of consistency in the construction. Most subjects used three or four nails to attach the midrail or the top rail, while some only used one or two nails to attach to the vertical posts.

Job Built Guardrail Structure Installation Recommendations

Orientation of Vertical Posts

Since the direction of the worker falling (*i.e.*, the applied loading) on the structure is not known, applied force in all directions should be considered when guarding a hole or opening in a floor or flat roof. In order to do this, the configurations of two of the posts located diagonally should be turned 90 degrees as shown in Figure 9 and Figure 10. This will ensure that two of the base fasteners are in shear while the other two will be in bending when the applied load is perpendicular to one of the top-rails. When the load is applied at the corners, then all four posts will have a combined shear/bending loading on the base fasteners. This configuration should result in a structure that is 34%-40% stronger when using 16d nail fasteners and 10%-19% stronger when using 3-inch all-purpose screws, measured under the same testing conditions. The posts should be fastened to the base using 3 or 4 fasteners each.

Fastening techniques

The overall strength of the structure increases when the ends of the rails overlap and are fastened to each opposing rail. The number of fasteners should be limited; more is not always better. Fasteners should be staggered if possible to prevent the wood from splitting under loading. The nail fasteners should be equally distributed into the board. When fastening into the short side of the 2" x 4",

Figure 10. Perspective View of Guardrail

Figure 11. Overlapped Rails and Fastener Placement

two fasteners should provide acceptable strength. When fastening into the wide side of the 2" x 4", three fasteners in a triangle configuration should provide acceptable strength. This is shown in Figure 11.

When constructing a guardrail, the overall strength can be maximized by using screw fasteners. Even though only three test subjects were used to reconstruct the job-built flat configuration using 3-inch coarse thread all-purpose screws, the data indicated that using the screws resulted in, on average, significantly stronger configurations that were built slightly quicker than the same guardrail system using duplex 16-d nails (Bobick *et al.*, 2010). The three test subjects that conducted these extra tests indicated that using nails was more typical, but that they often used screws on the job and felt that this was a fair test.

Future Work

An additional point to consider is that there are higher quality screw fasteners that are made of high-strength steel and have a self-drilling capability. These particular fasteners have been subjected to independent laboratory tests, as contracted by the screw manufacturer, to determine their strength characteristics when installed in different materials. The use of this type of fastener could result in a stronger guardrail system that may be installed quicker than the typical all-purpose screw fasteners. Additional laboratory testing using these more sophisticated fasteners is planned for the future.

Conclusions

Based upon the aforementioned results, it is possible to construct a job-built OSHA compliant guardrail, as evaluated with the described OSHA 200-lb drop test. The job-built guardrails can be safely constructed using construction-grade 2" x 4" lumber and appropriately sized nails or screws.

The job-built guardrails could have inherent weaknesses due to the non-homogenous building material. This limited study exposed multiple weaknesses and strengths. With proper planning, some of these weaknesses can be engineered out to build the strongest temporary structure possible. The method of constructing, the type of fasteners, and the fastening techniques used are key planning factors to build an OSHA compliant guardrail structure. The overall success of constructing a job-built guardrail structure is proper planning. Good safety practice requires that job-built guardrail systems be constructed of new 2" x 4" lumber for the system to obtain the maximum possible fastening strength. The practice of re-using old materials is unsafe and should be avoided.

Acknowledgement

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Disclaimer

The findings and conclusions in this report are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health

The National Institute for Occupational Safety and Health (NIOSH) is a research agency. It does not conduct any type of certification testing of fall-protection or fall-prevention equipment.

Mention of any company names or products is for informational purposes only, and does not constitute any endorsement by NIOSH, or any agency of the Federal government.

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In This Issue:

Falls and Fall Protection in Construction

In The Next Issue:

Residential Wood Decks

Editorial

Wood Design Focus has always provided current industry information. Most topics in this journal have discussed technical aspects of design and the use of wooden building construction. As we design and construct buildings, engineers and architects often tend to focus on the materials and methods of construction. However, the moving forces behind these materials and methods – notably the human workers – often receive little attention. Construction safety is one of the most important worker issues. Conducting work in a safe manner affects worker productivity, worker attitudes and overall worker health. Many times, the discussion of human and structural loading related to construction safety is forgotten or relegated to a lower position.

I began conducting safety-related research about eight years ago. Initially, I was invited by a colleague to contribute to a proposal for a NIOSH safety center. That center has now evolved into the Center for Innovation in Construction Safety and Health (CICSH), under the Occupational Safety and Health Research Center (OSHRC) through Virginia Tech. My colleague challenged me to think differently about my research. How can the understanding of the mechanics of wood influence the safety of construction workers?

I began looking at the effects of lateral buckling of wood composite I-joists as a possible initiator of falls from elevation. At this time, I began to grasp the current severity of falls in construction. Other researchers have gone so far as to call the number of fatalities an epidemic. As I continued pursuing safety research, I began to realize how useful the design of wood structures is to the safety field. Currently, I am the lead investigator in a project examining the use of personal fall arrest systems in residential construction, which is described in this issue. I also currently serve as the Co-Director of the Center for Innovation in Construction Safety and Health (CICSH).

I find myself explaining to both engineers and safety professionals (even once to my department head) why I am researching safety and the importance of involving engineers. One of the important aspects called Prevention Through Design (PtD) directly involves the re-design of buildings to create inherently safer work environments during construction and after construction. There is a genuine need in safety for the innovation and creativity that structural engineers and architects possess. The intersection of safety and engineering is an exciting area of study – combining experimental mechanics, human factors, experimental design, industrial psychology and building construction.

This selection of authors represents a variety of researchers and professionals looking at the intersection of safety and engineering. These articles can help promote worker safety, which ultimately improves worker productivity and health. This issue of Wood Design Focus is part of a two-year Falls Campaign effort to bring attention to the problems associated with falls from elevation. More information is available at http://www.stopconstructionfalls.com. I hope you will be inspired by these articles. As always, we have provided contact information for the authors if you have questions or desire more information.

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