Unstable Shelves Put the Shake in Shakespeare

By Betsy Wilkinson, P.E., S.E. and Alberta Comer, MLS

A quiet day in August 2010. The Library Dean, Alberta Davis Comer, MLS Indiana University-Bloomington, was at a retreat when she received a call that book ranges had fallen. Relieved to find that no one had been seriously injured, the Dean left immediately for campus which was about 15 minutes away.

At the library, the Dean proceeded immediately to the second floor stacks where the ranges had fallen. There she found five ranges, each with 13 sections, collapsed and two more ranges precipitously leaning. Later it was determined that about 20,000 books were on the floor. The Dean called the Facilities Department and asked for their assistance in assessing the situation. Facilities responded immediately. After the General Construction Supervisor reviewed the situation, he determined that the area was unsafe for public or staff. Since each library floor is connected by 2 elevators and 4 stairwells, it was not practical to block off the entire floor. An electronic alert was broadcasted to campus that the Library was closing for the rest of that day and would also be closed the following day to allow time for safety measures to be put in place.

Cunningham Memorial Library (CML), built in 1973, has five floors. Three floors above ground and two below, the library holds about 1 million print items. Shelving, typical of libraries of this age, was erected without bracing, although top, lateral bracing was added a few years ago.

In 1989, twelve ranges of shelves, holding an estimated 20,000 books, collapsed in the Libraries Annex of Columbia University. Some of the books went through the window, falling three stories to the ground. The culprit in this mishap was determined to be the lack of laterally braced shelving. Many of the Annex books were fragile and about five thousand volumes were either lost or damaged (Gertz). The information available in the literature is mostly about earthquake-related damages and how to make library structures safer. For example, an article in the *Journal of Library Administration* discusses non-structural earthquake hazards including "unsecured or unbraced library shelving, any library materials which are stored on shelves over 5 feet from the ground" (Beinhoff) and states: *Probably, the only unique furnishing in the library which will not be fully addressed in a regular earthquake preparedness seminars (sic) and which needs to be examined by a trained professional is the library's shelving.*

Although the CML shelving collapse was not caused by an earthquake, it was still important to hire a professional to inspect all of the library shelving. A structural engineer was hired to determine the cause of the ranges falling at CML, and to appraise the current status of all library shelving.

An Engineering Perspective

Upon arrival to Facilities Management for a regularly scheduled meeting, Betsy Wilkinson, P.E., S.E. of KIVA Structural Engineers, was informed that the university architect, Scott Tillman, AIA, wanted to make a detour to the CML building before continuing with their previous plans. This was the same morning that the ranges tipped over. Upon first inspection, it appeared that one range tipped, precipitating a domino effect of the adjacent ranges. The only thing that had stopped the chain of motion was the remaining bracing straining to give up as well. The library staff was in the process of removing the books that still pressed against the remaining upright ranges. The initial response was clear: "What caused this?" and "How do we prevent this from happening again?"

The answers to these questions are as important to Indiana State University's CML as they are to any library. Ms. Wilkinson set about looking at sources of the instability that caused this specific event but felt it was important to also investigate other potential causes. For this she turned to the 2006 *International Building Code* (IBC), as well as the record drawings for the CML structure and the range manufacturer's literature. There are three potential direct causes for an event such as this: asymmetric shelf loading, floor deflection, and seismic (earthquake) forces. Each of these influences introduces a horizontal force that causes the ranges to tilt. The additive effect is the sum of all three influences. The largest of these forces is the seismic force, followed by shelf asymmetry and then floor deflection. Each cause has unique contributing factors.

Floor Deflection

In general, a library structure is laid out with a repeating grid of columns. This facilitates the placement of ranges and aisles to maximize the space. The columns are often laid out in a square grid, or very close to square. The floor framing is often concrete or composite steel construction because these systems are cost effective for construction in repetitive framing patterns and have excellent sound and fire resistance qualities. The shelf sections are considered movable at any future point in time, so would be classified by the building code as a live load. The code minimum live load capacity required for library floors is 150 pounds per square foot (psf) (2006 IBC, Section 1607, Table 1607.1 and footnote b). This is a relatively high live load compared to the average building, but it is appropriate for a library due to the expected use of the floor space.

continued on next page

Betsy Wilkinson, P.E., S.E. is a Principal and structural engineer with KIVA Structural Engineers. She may be contacted at ***kivase@cs.com****.*

Alberta Comer, MLS is the Library Dean at Indiana State University. She may be contacted at ***alberta.comer@indstate.edu****.*

The online version of this article contains detailed references and resources. Visit **www.STRUCTUREmag.org**.

Courtesy of Cunningham Memorial Library PR Unit.

The industry standard for book shelves requires them to hold up to 50 pounds of media per linear foot (plf) of shelf space, or 50 pounds per cubic foot (pcf) of shelf volume (Shelton). The expected maximum weight of a typical 3-foot wide shelf section that has seven shelves on each side is about 2,150 pounds when fully loaded.

In the CML building, the floor framing system used concrete columns on a 22 foot-6 inch square grid supporting concrete beams, joists and slab in a repeating pattern. This structure created a predictable pattern of floor deflection and rotation. In other words, for the CML, if a given shelf was precisely located where the floor slope calculated to be the greatest, then it could contribute a sideways deflection (tilt) of approximately ⅛ inch at the top of a 7-foot 6-inch tall shelf section relative to its base. These shelf sections are not located *exactly* to achieve this much tilt; however, some fraction of this much tilt will exist in each shelf section depending on their as-built locations relative to the building columns. Floor deflection is unavoidable because the structure has to deflect and rotate in order to support any load.

Shelf Asymmetry

Shelf asymmetry is conceptually simple: too many books on just one side. As long as the shelf is always loaded symmetrically with identical weight distribution on each side, this effect can be avoided, right? This is not a realistic expectation for a working library. Even if a shelf could be identically loaded on both sides, it would become partially asymmetric as soon as a patron wanted to check out a book. Let's assume that the shelves on one side are all loaded with books up to the industry standard (50 plf of shelf space), while the opposite side is empty. This is what would be considered complete asymmetry. The effect of this complete asymmetry will introduce a sideways deflection. The magnitude of this deflection depends on the strength of the vertical uprights, which is specific to the range manufacturer and is proprietary information.

Simply put, if one is choosing from two range manufacturers, Company A and Company B, their prices would be directly related to their material expenditures. Company A offers "excellent resistance to unbalanced loading" while Company B offers "economic use of materials, saving you money." The vertical uprights for A would be strong and stiff with a small deflection when the shelf is asymmetrically loaded, but then how often does complete asymmetry occur in practice? Company B offers a monetary savings in exchange for vertical uprights that flex more when asymmetrically loaded. There are manufacturers that fall everywhere in between these two extremes, so this evaluation must be specific to the manufacturer that supplies a library with its system of ranges.

For the CML, Ms. Wilkinson took measurements of the vertical uprights and made conservative assumptions for the material strengths so that she could estimate the deflection to some reasonable degree of accuracy. The resulting sideways deflection (tilt) was estimated to be approximately ¾ inch at the top of a 7-foot 6-inch tall shelf section relative to its base. If the shelves have partial asymmetry (a more balanced distribution of weight), then some fraction of this tilt will exist until complete symmetry of weight distribution is reached.

Seismic

Imagine standing on a rug while several people on each side of the rug pull it back and forth. This is what happens during an earthquake. You must react to the motion with a compensating force in the direction of the motion in order to re-align your center of gravity with your feet. This is perhaps easier if you are standing with your feet apart and your arms out to brace you against impact with other objects. Now, imagine you have to stand with your feet together and your hands at your sides. Not so easy! This is how it is for the library ranges. They are tall and narrow and, without top bracing, would tip over when the "rug" is pulled.

This appears to have been the case at California State University in 1994 (CSU Northridge, 2/10/2011), where a 30-second earthquake eliminated the university's library service for 25,000 students for a period of eight months, and restricted the full services for over four more years while new facilities could be built. On January 17, 1994, the Northridge Earthquake hit Los Angeles, California. No one was seriously injured because the university was on a break between semesters; however, 600,000 volumes were thrown off their shelves and had to be stored and reorganized. The lessons learned not only changed the structural engineering of steel connections, but also changed library standards for shelving.

The seismic force must be determined for a typical shelf section. The seismic force is directly related to the weight of the shelves plus the books. The seismic analysis revealed a need to establish a pattern of bolted bases and top bracing. Not every row required bolting because the top bracing helps deliver the forces to a bolted row. For every row that was bolted to the floor, up to four more rows of ranges could be braced to that bolted row to use it for support during an earthquake. In addition, some of the bracing was bolted directly to building columns to eliminate some of the required floor bolting.

Cause of Collapse

What caused the collapse at the CML building? On that August day there was no recorded earthquake of any significant magnitude; however, the first two causes proved enough to make the difference. It was determined that a combination of two factors initiated the first shelf to fall over, which created a domino effect on the remaining shelves. At the time of the collapse, the books were being reorganized and re-shelved. In addition, some top braces were missing their bolts to the ranges. The shelf sections were also not bolted to the floor. It is believed that the initial row of shelves fell due to temporary shelving asymmetry and floor deflection. When a top brace was removed, this released the top of that shelf allowing it to deflect and then become unstable.

Timing It Right

Through the cooperation of Mr. Tillman and Facilities Management, KIVA Structural Engineers created contract documents for competitive bidding. The winning contractor, MSI Construction, was required to place the bolts and bracing system for all five levels of the library within the three weeks of Christmas break, so there would not be any interruption in student access to library materials while classes were in session. The noise and material storage would have otherwise proven to be an unacceptable imposition to library patrons.

Nick Roman with MSI Construction maintained contact with Ms. Wilkinson, who was to be on call as needed in order to clarify bolting and bracing requirements and minimize any delays. Various university staff, Alberta Comer (Library Dean), Debra Robinson (Library Assistant), Paula Huey (Library Assistant), and Scott Tillman (University Architect) were also on call when questions regarding costs, changes, or handling of books came up. Mr. Roman's crew of skilled laborers did an excellent job of installing the bolting and bracing system to support 9,030 linear feet of ranges, while maintaining their commitment to the schedule and budget.

Conclusion

When a library suffers a shelving collapse, no matter the reason, it is important to consult a structural engineer. Such a proactive approach may prove beneficial, especially as libraries continue to age and building codes under which they were built become outdated. Beinhoff reinforces this concept, writing that if the bracing was installed before the early 1980s it might not meet today's seismic code, and that more damage might be sustained by having improperly braced shelving than if there were no bracing. Beinhoff states: *Getting trained professionals in to examine and recommend a method of properly securing and reinforcing library shelving is essential because only someone with engineering experience will be able to understand how library shelving will react to the different stresses caused by an earthquake….*

In a 1996 article, author Guy Robertson, a Canadian librarian, reinforced this concept when he wrote that a shelving risk analysis may be needed, especially since libraries "move things to different locations, revise and reinstall." Thus, the shelving system that was initially installed loses its integrity over time.

Although the literature may not reflect either the magnitude of the problem or the importance of the subject, having just witnessed such an incident has convinced these authors that libraries need to carefully assess their shelving situation.▪

References

Beinhoff, Lisa A. (2000) Library earthquake preparedness planning, *Journal of Library Administration*, 31: 1, 67-83

Gertz, Janet E. (October 1992) After the fall, *Conservation Administration News*, 51: 1-2, 30

International Code Council (March 2006, Fourth Printing) 2006 *International Building Code*, International Code Council, 285-286

Shelton, John A. et al (1990) Seismic Safety Standards for Library Shelving, California State Library Manual of Recommended Practice, *California State Library Foundation*, 7

Robertson, Guy. (February 1996) Shelving and safety: An overview, *Feliciter*, 42: 33-36.

Online Resources

CSU Northridge, "Oviatt Library Earthquake Damage". California State University Northridge. 10 Feb. 2011 **http://library.csun.edu/About/Quake**

USGS, "Historic United State Earthquakes". United States Geological Survey. 10 Feb. 2011, 10 Feb. 2011 **http://earthquake.usgs.gov/earthquakes/states/historical_state.php#california**

USGS, "Latest Earthquakes in the USA – last 6 months". United States Geological Surve. 10 Feb. 2011 **http://earthquake.usgs.gov/earthquakes/recenteqsus/**