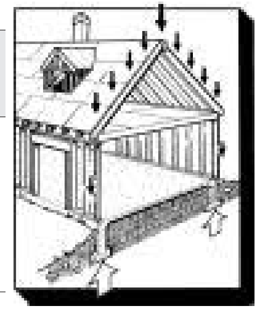
Shake, Rattle & Roll: Vibrations in Long Spans



by Harris Hyman, P.E.

When I was just getting started in practice with my shiny new P.E. certificate, I was at lunch with a group of engineers. The conversation turned to war stories of errors and jobs that went sour. I was kind of shocked and said so. One of the older engineers just looked quietly at me for a long pause and then sighed. Without a word, he eloquently said, "You'll learn, kid."

And learn I did, even though I've been pretty lucky over the years. Like most engineers, I *do* make a conscientious effort to do careful work, but the low incidence of serious problems is really due as much to luck as to my own efforts. There's no other word for it, even though our culture is extremely reluctant to recognize *anything* except individual effort and responsibility.

One day my luck ran out. The project was a small town fire station on an extremely difficult site: a tiny lot that sloped down between two streets with about 30 feet of grade difference. The fire equipment was on the lower level, and a community hall was on the upper level. On both levels, the space was a clear span — about 60x80 feet for the lower level and about 50 feet square for the upper level.

The building posed some interesting structural problems. First, there were the clear spans, particularly the community hall above the engine room. This could be heavily loaded for a town meeting, party, or wedding. Then there was the hillside, which had to be kept out of the fire station with a retaining wall that didn't have much space behind it for a footing or tiebacks.

For the retaining wall, we used a "box caisson" — an 8x8-foot reinforced concrete box, about 20 feet high. The box was filled with crushed stone and provided a stable weight to hold back the upper level with vehicles parked on it. This was an innovation for rural Maine, and I was quite pleased and proud of it.

The clear span had a much more ordinary solution. The 60-foot dimension was spanned by three large (24 inches deep) steel beams 20 feet on-center. Across these, 20-foot-long steel bar joists were laid 4 feet on-center. Across the bar joists, a steel deck pan was laid, and this was filled with concrete.

The solution was straight out of the book — solid, conventional, and up to code (even though the community had not yet implemented a building code). We had an excellent contractor who could handle steel and concrete, as well as rough and finish carpentry. He was smart enough to come up with some practical suggestions without redesigning the building to *his* tastes, and the whole job went well — on time and on budget.

The Party's Over

When the job was completed, the fire company held a benefit dance to inaugurate their new building. Our office bought the obligatory block of tickets, and even thought we might go. Then, on the Saturday morning of the party, my partner calls frantically, "The building is coming apart!" I went down, where some people were preparing for the party; the floor had a distinct shakiness. I was almost physically sick inside, but managed to smile weakly and tried to appear confident that I "would check things over."

I raced back to the office and reviewed my calculation files, but everything looked okay. I cross-checked my calculations against some rough approximate solutions and still everything looked okay. The upper floor did miss the code threshold for stress and deflection by a couple of percent, but this is not unusual and, besides, I was using the code as a voluntary guide rather than as a legal mandate.

I then returned to the site, and got the sponsor to move the food tables into a square in the center of the space. This kept people away from the center and lessened the stresses, and the building appeared to be a little less shaky. There was no physical damage like cracks or excessive deflections, so it looked okay. The party was held, and everyone had a good time despite the uneasiness.

The analysis continued over the weekend, and on Monday the town manager asked another engineer to review the situation. This engineer was in partnership with his brother, also an engineer; he specialized in electrical and acoustical engineering. They were coming back from another job when they visited the site. The engineer found nothing perceptibly out of order, but the brother — the acoustician — noticed that the floor vibrations had a frequency of about 1 *hertz*, or one cycle per second.

Bad Vibes

Human beings move at about 1 or 2 hertz. Our breathing is about 1/2 hertz, our hearts beat at 1 hertz, and we walk at 2 hertz. *The building was tuned to respond to human movement!* The stresses and deflections were okay by the book, but we had a serious vibration problem!

The code manual gave no advice for vibration, but this was clearly a design error, as it reduced the serviceability of the building. The steel joist design manual hinted at some possible vibration problems with 30-foot spans and 8-inch concrete decks, but our joists were only 20 feet long and our deck was 6 inches thick. But a little more investigating showed the problem was really in the steel beams. These were stiff enough, but were *very* flexible. This was a little hard to believe for W24x117 steel beams, but facts were facts.

Next, I called up the American Institute of Steel Construction in Chicago, and they referred me to the vibration systems guru: Tom Murray of Virginia Tech in Blacksburg. We had a couple of long conversations and Tom gave me a graduate-level course in building vibrations over the phone, and sent me a couple of inches of reports and studies. I learned a whole lot about vibrations that week.

As an old bridge engineer, I should have realized that vibration is a potential problem area, but ordinary buildings don't usually vibrate and I had failed to consider it. The same is true of most of the engineers I have talked with since. Bridges are subject to bouncy moving vehicles and these are *always* checked for vibration, but buildings? Not unless they contain heavy machinery.

The Fix

The problem was solved with diagonal braces on two of the beams, effectively shortening and stiffening the span and raising the natural vibration frequency above 5 hertz. This was way above the realm of human movement and the problem went away. A post in the center of the beam would have been better, but the fire department didn't want to give up the unobstructed space in the engine room. We had the braces fabricated at our own expense and I personally installed them with the help of a welder. This seemed like the reasonable thing to do as well as good business. However unwittingly, we had brought the problem about and it was only fair that we solve it. Our final cost was about $1,000, a lot of embarrassment, and a whole lot of anxiety. Now, seven years down the line, it's pretty much forgotten, but not by me.

So What?

Besides making an interesting story about the fallibility of the engineer, what's the point here? There are two. First, there are situations of failure that go beyond the building codes. Problems the codes are supposed to prevent still happen occasionally. We're not perfect, and neither are our codes. While the codes specify radical overdesign for some things, there are other areas, like vibration, that are completely missed. Our buildings must *work*, not just meet code. This community hall clearly did not work.

The other point is structural. Vibration problems occur with heavy dead loads, moving live loads, and long spans. This is the very situation with thin-slab radiant floors, where heating pipes are buried in a couple of inches of concrete. Although I've never heard reports, calculations suggest that radiant floors with spans over 20 feet can become very bouncy and vibrate uncomfortably. Do you know about any of these? Please let me know. ■

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