THE BANGING BOLT SYNDROME

Unexpected loud noises can cause high anxiety for building owners and tenants

Exterior view of an office building in Santa Clara, CA, exhibiting the banging bolt phenomenon

By Robert L. Schwein

GIVEN CALIFORNIA'S PROPENSITY FOR EARTHQUAKES, tenants are understandably sensitive to extraneous noises in their building. The rattles in chiller unit piping, vibrations from elevators, and creaking of curtain wall attachments all contribute to occupant unease and tenuous lease renewals for the owner.

One not so often reported situation involves single-plate connection (shear tab) bolts in gravity connections slipping into bearing sometime during the early service life of the building. This may be a one-time phenomenon, or it may occur more than once, such as with thermal or service loading.

Such was the case in a 12-story office building in Santa Clara, California that is occupied by a software development company. After completion in 1998, it began experiencing random "loud bangs," sometimes accompanied by noticeable vibrations. The banging has continued for several months with increasing tenant concerns. The noise has been described as "bangs, thumps, pipes contacting one another, vibrations, water hammer, etc." by the tenant's personnel. No apparent consistency has been established with weather, sun exposure, wind, etc., except that most of the reports have come from the fourth and ninth floors. No positive differentiation has been made about whether the noises have come from the floor or the ceiling.

The building was designed with perimeter moment connections. Typical bays are 25' by 40' and are subdivided by girders running in the 40' direction. The typical, non-moment joints are simple bolted shear connections (single-plate) containing from five to eight, 7/8" diameter, ASTM A325 high strength bolts. Fluted steel decking spanning 12.5' supports reinforced lightweight concrete slabs. Shear studs connect the slabs to the steel frame for composite action.

Approximately five months after the building frame was completed in April 1998, the noise occurrences began. The noises have been reported in every month except October 1998 and February 1999. Initially, attention was focused on the welded moment connections and the attendant lateral bracing of the lower flanges. Sample inspections of these connections showed no abnormalities. The HVAC systems were cycled to criteria beyond their normal operating ranges in an attempt to replicate the banging noises possibly being caused by contacting piping or water hammer effects. The noises could not be reproduced.

An adjacent twin building constructed in 1987 has never experienced the problem. It is also a steel moment frame structure. Its steel frame has shorter spans than the subject building does. Even the granite and glass cladding systems are similar.

So why is one building experiencing such problems while the other structure remains dormant?

A literature search was conducted to determine if this phenomenon had been studied in the past. Three articles briefly men-

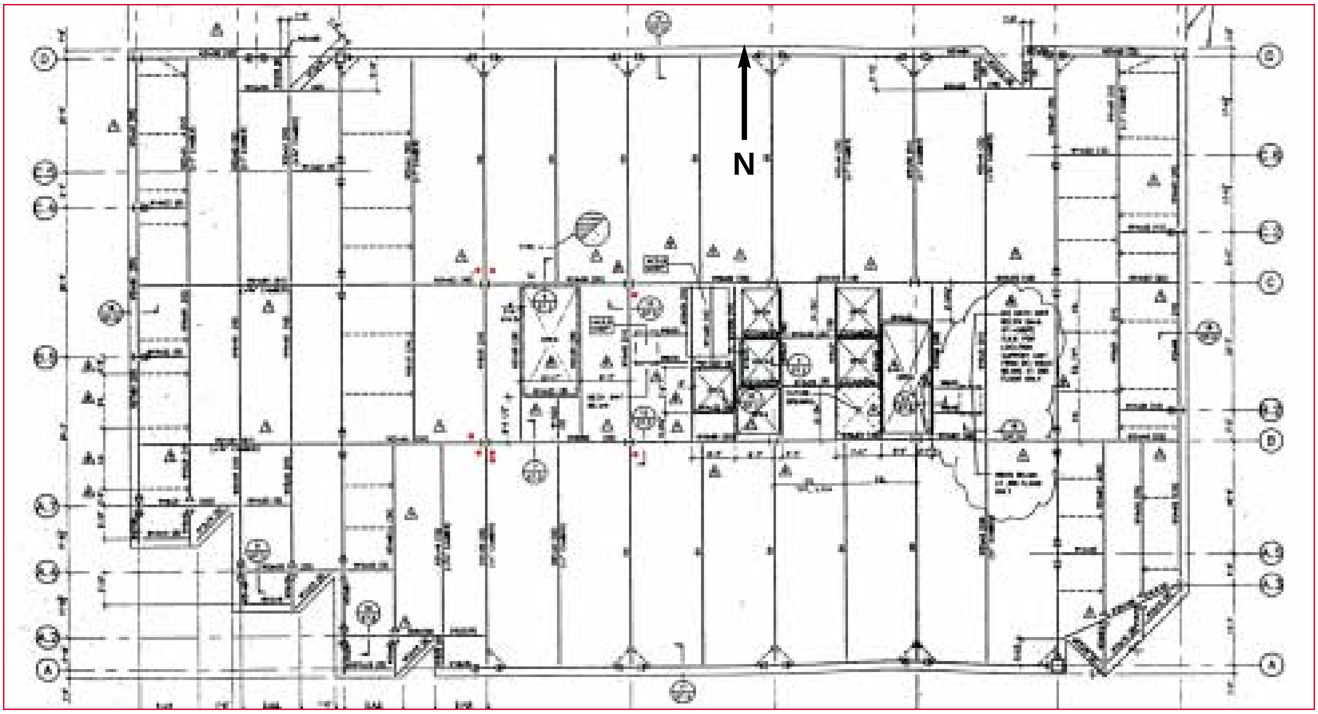

Figure 1: Fifth floor framing (red dots indicate de-torquing noise events)

tion related issues:

- "High Strength Bolting: Recent Research and Design Practice," by Birkemoe, P.E., *Proceedings of W. H. Munse Symposium on Behavior of Steel Structures - Research to Practice*, by W. J. Hall and M. P. Gaus, Editors, ASCE, New York, NY.
- "Lack of Fit in High Strength Connections," by Mann, A. P., & Morris, L. J. (1984), *Journal of Structural Engineering*, ASCE, Vol. 110, (No. 6; June), pp 1235-1252.
- "Compendium of Design Office Problems," Committee on Design of Steel Building Structures of the Committee on Metals, Structural Division, *Journal of Structural Engineering*, Vol 118, No. 12, December, 1992.

These papers reported on building noises and their probable cause of bolts slipping into bearing with the attendant noise; however, they did not study the actual mechanism which may have induced stresses into the steel members to cause the joint slippage. Colleagues from various parts of the United States were contacted for their experience with this phenomenon.

Two other structural engineers who I spoke with, Michael Koob of Wiss, Janney & Elstner Associates, Northbrook, IL and Ralph Richards, University of Arizona, had this same occurrence in their investigations, typically with long runs of non-moment, gravity loaded, bolted connections.

The concrete mix designs and concrete test reports for the deck placements were evaluated. The concrete mix design contains a lightweight aggregate from Baypor in Port Costa, California and Olympia sand from Felton, California. These aggregates have good drying shrinkage properties as long as the water/cement ratio is held low. No drying shrinkage tests were run either prior to, or during the project. This is not uncommon on routine projects such as this if the aggregate sources have a history of satisfactory shrinkage. The average slump value for all floor slabs was 5.4", slightly in excess of the 4½" maximum slump limit. This would result in higher-than-expected 28-day drying shrinkage values (probably in the 0.045 to 0.055% range). The average compressive strength for all floor slabs was 3555 lbs. per square inch, which complied with the requirement of 3000 lbs. per square inch at 28 days. No correlation was made with these values and the fourth and ninth floor noise events.

The structural plan drawings and details were studied in an attempt to relate the reported events with particular locations in the steel framing. The reported noise locations were also plotted on plan drawings of each floor. There was some concentration of reported events in the south-central area of the building on the fourth and ninth floors; however, no specific conclusions could be drawn.

After the above research, it was decided to alter the focus of attention from the welded moment connections to the bolted gravity connections. We noted that Lines B and C in the east-west direction and Lines 2.5, 5 and 6 in the north-south direction were continuous runs of approximately 180' and 108',

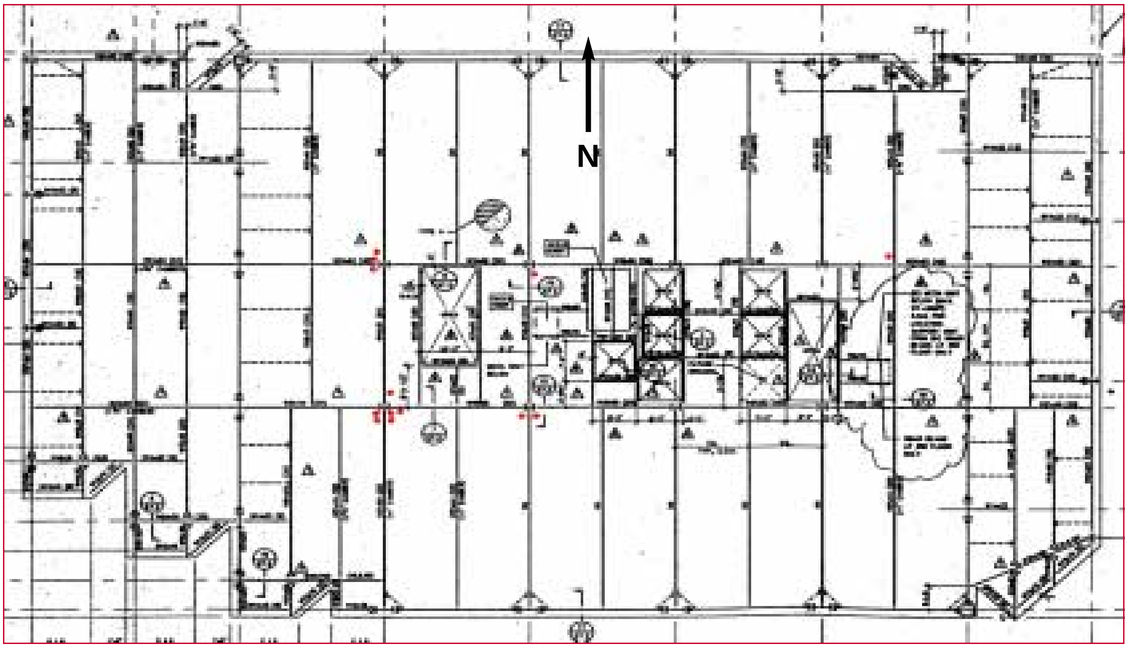

Figure 2: Ninth floor framing (red dots indicate de-torquing noise events)

respectively. Postulating that drying shrinkage of the concrete deck might be transferring compressive loads into the steel framing, these long runs seemed to be candidates for study. It was decided to loosen selected and accessible bolted connections in an attempt to recreate the reported noises. Six interior connections on each of the fifth and ninth floors at Lines B and C, 2.5, 5 and 6 were selected.

Access was gained to the connections and the fireproofing removed from the subject bolts. The accessible bolts on the four sides of these connections were manually loosened with a calibrated torque wrench, beginning with the central bolts and working towards the top and bottom sequentially. The loosening torques were measured and recorded where possible. Some of the connections were inaccessible due to HVAC equipment and firewalls.

After observing and hearing a few of the noises, they were classed into two groups: "pings," a metallic high-pitched noise and "bangs", a heavy low-pitched noise accompanied by distinct vibration. Of the 105 bolts tested, 13 pings and eight bangs were recorded. Twenty-one percent of the bolts tested responded with either a ping or a bang of varying magnitude. The majority of the noises were detected on the long bay (40' dimension) north-south members in the building. Figures 1 and 2 show the events graphically. The torque values averaged approximately 350 lb.-ft. to 400 lb.-ft. One typical bolt was removed from a joint. It was a $\frac{7}{8}$" diameter by 2$\frac{1}{4}$" long ASTM A325, high strength type. It was a button-head twist-off type bolt. It carried an upset "n" symbol on the head along with the A325 marking. The "n" is believed to be the mark of the Nucor Fastener Company. Hardened washers were present beneath the nuts. All of the bolts were re-installed to a 200 lb.-ft. torque level using a calibrated wrench, which represents a nominal snug-tight condition.

Based on the analysis and test results, it is highly probable that the reported random noises which have been occurring in the building are the result of high strength bolts slipping into bearing due to axial compression loading of the steel frame beam members. Drying shrinkage of the lightweight concrete deck slabs is likely inducing this loading.

Portland cement concrete is mixed with water in excess of that required for hydration. This facilitates mobility and workability of the plastic mix such that it can be readily mixed, transported and placed in the forms. Some of this water is used up in the chemical process of hydration of the cement and the excess leaves the concrete through evaporation. As the pore spaces in the paste lose their water, surface tension tends to shrink the surrounding paste, causing shrinkage of the hardened concrete. This shrinkage diminishes in time in an asymptotic manner. Generally, between 65 and 85% of the ultimate drying shrinkage occurs in the first year.

The steel framework is anchored to the concrete through the fluted metal decking and the shear studs, which are installed for composite action. As the concrete shrinks, the steel tries to restrain it, causing compression in the members and joints. When these forces exceed the friction supplied by the bolts in the gravity members, the bolts suddenly slip into bearing with the attendant noises. The smaller pings are likely individual bolts slipping, and the large bangs with accompanying vibrations are a group of bolts which all slip into bearing at one time.

The non-moment resisting shear connections are the most likely to experience this phenomenon. The moment resisting connections with welded flanges and bolted webs would be less prone to this bolt slip because the flange welds, being stiffer, would attract and resist most of the strain before the load would cause bolt slips in the web. Based on the plots of noises from the tests shown in Figures 1 and 2, it is apparent that most of the slips occurred on the longer span members (40') running in the north-south direction. This would be expected due to the longer members attracting greater compressive loads with less chance for relief at the fewer number of joints. This seems to correlate with the tenant reports as well.

Non-slip critical bolted connections should be made with high-strength bolts tightened only to a snug-tight condition

The third through ninth floor steel framing is virtually identical in plan; however, the members vary in section size as the building ascends. The concentration of the events at the fourth and ninth floors with a lack of reported events on the intermediate floors suggests that the concrete may have been placed at a higher water/cement ratio, hence increasing the amount of drying shrinkage and attendant stress in the steel members.

The only apparent means to eliminate the noises would be to loosen all of the bolts on all of the gravity connections in the building and return them to a snug-tight condition. This would be a huge undertaking, requiring the removal of many fire walls, HVAC systems, plumbing lines, electrical and computer wiring, etc. as well as being highly disruptive to the tenant operations.

The Research Council on Structural Connections (RCSC), *Specification for Structural Joints Using ASTM A325 or A490 Bolts*, recommends that non-slip critical bolted connections be made with high strength bolts tightened only to a snug-tight condition. A similar recommendation is found in the AISC specification. The bolts used in this structure are an A325 bolt of a self-regulating torque type design in which the assembly is tightened through the nut and reacted through a splined tip on the threaded end of the bolt. The assembly then twists off at a torque value that corresponds to the proper tension. The calibrated wrench torque that was measured (375 lb.-ft. average) when the bolts were loosened appears to be about 60% of the torque required to fully tighten the bolts (approximately 715 lb.-ft.). It is probable that this level of pretension is more than required for the minimum condition of snug-tight and may have contributed to the banging bolt phenomenon.

In the case at hand, the installed pretension combined with the slip resistance on the faying surfaces (which were not specifically prepared to achieve any specific class of slip resistance) results in some nominal frictional resistance that initially carries load. In many cases, this frictional resistance is overcome during construction. However, in some of the referenced cases, the frictional resistance was not overcome until the building was in service. In several instances, the attendant slip was accompanied by noise.

The simplicity of using only one type of bolt on a job for both slip-critical and bearing connections probably imparts some economies as well as eliminating confusion by the ironworkers. Common practice in erection is to use the same impact wrenches on all bolts. If necessary, noises such as those described can be minimized by installing the tension-control bolts to the snug-tight condition, but without actually severing the splined end. On average, this will reduce the actual pretension in the joint and increase the likelihood that the connections will slip into bearing well before occupancy.

In the end, however, the conditions creating the noises are not of structural significance and in no way affect the integrity of the building's structural system nor compromise its ability to resist the seismic, wind or gravity loading that it was designed to accommodate. Given this, it was recommended that no corrective action be taken. The noise events will probably continue at a lesser and lesser rate for another year or so and then cease as the concrete shrinkage diminishes with time and more bolts slip into bearing.

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