Seismic Design and Performance of Metal Buildings

By W. Lee Shoemaker, P.E., Ph.D.
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The performance of metal building systems in earthquakes has been excellent over the years because they are strong, flexible and light in weight. The low mass and high ductility of a metal building provides some of the intrinsic qualities that enhance their resistance to seismic action. Surveys of metal building performance after recent earthquakes have documented this. But this does not mean we can rest on our laurels because new code requirements may unfairly penalize these types of structures.

Lessons From the Past

Investigations of earthquakes have helped us learn how metal buildings actually perform in seismic events and if any improvements can be made to enhance their performance. The major earthquakes that have provided the most insight into the performance of metal buildings over the past two decades are summarized in Table 1.

Coalinga Earthquake (1983)

On Monday, May 2, 1983, at 4:42 p.m., an earthquake of moderate magnitude struck near the rural oil and farming community of Coalinga in the San Joaquin Valley, California. The quake measured 6.5 on the Richter scale and the epicenter was approximately nine miles north-northeast of Coalinga.

Coalinga is a small town with a population of 7,000. The earthquake devastated the city's central business district. Most of the structures in this area dated from the early 1900's and were constructed during the oil exploration boom. They were built mainly of unreinforced brick masonry. Recent commercial development had occurred primarily outside the central district.

A survey of engineered buildings was carried out after the Coalinga earthquake that included the investigation of 37 metal buildings. All of the metal buildings were typical of those designed to resist seismic forces with a moment frame in the transverse direction and a braced frame, using rod or cable bracing, in the longitudinal direction. The metal buildings all performed well, although a few lessons were learned.

The survey summary of these buildings stated:

> "there was no visible damage to any moment frame, but one building had a broken rod and one had a broken cable [brace]." There was strong evidence that the sidewall sheathing participates in resisting shear, even though it is generally not designed to do so. In several small buildings (50- to 60- foot span), sidewall

bracing was found to be missing altogether, and still there was no damage to the buildings. As further evidence of the beneficial effect of metal sheathing, a one-bay building at the airport ,with no sides showed, severe distortion off the column webs with consequent loosening of the brace rods. In some larger buildings, some rods or cables were found to be loose and, in two cases, were broken. The worst damage was observed in a wide building still under construction that had rods in only one wall. This effectively doubled the load on the bracing and caused the buckling of a corner column."

Whittier Earthquake (1987)

On Thursday, October 1, 1987, at 7:42 a.m., an earthquake of moderate magnitude occurred northeast of Los Angeles, California, near the city of Whittier. The quake measured 5.9 on the Richter scale and the epicenter was approximately nine miles northeast of Los Angeles.

A survey team sponsored by MBMA investigated building performance and filed a report with their findings. The majority of the damage was in the "uptown" area of Whittier over a six-square-block area. The damage occurred primarily to un-reinforced masonry (brick) buildings which were built in the 1920's.

Only one metal building located in the area was surveyed. That building was constructed in 1972 and was located two miles from the uptown Whittier area. The building, which had two sections with different eave heights, was approximately 120 feet x 120 feet. The higher section had a partial second floor. The rigid frame was three spans (two interior columns) with 10-ton cranes in each span. All overhead doors and cranes operated without any problems following the earthquake, even though the building supervisor indicated that one exterior column was approximately 1 ½ inches out of plumb in the weak direction. Portal frames were used to brace large doors, and diagonal bracing was used elsewhere to brace the building in the longitudinal direction. "Sidelaps were fastened with aluminum pop rivets which were sheared, indicating the wall panel tried to resist the forces in diaphragm action. Fortunately when the diaphragm failed, there were the diagonal rods in this bay to take up the load. Flange braces were installed on one side of the web only and a slight compression buckle was observed in the brace at the haunch area above the office."

Loma Prieta Earthquake (1989)

On Tuesday, October 17, 1989, at 5:04 p.m., the first major earthquake to strike Northern California in 80 years rocked the San Francisco Bay area. The quake was centered in the Santa Cruz Mountains near the summit of Loma Prieta Mountain, 60 miles south of San Francisco. The quake measured 7.1 on the Richter scale.

A survey was conducted in the San Francisco area cities of Hollister, Watsonville, Gilroy, and Soquel, California to determine the performance of metal buildings during the earthquake. These cities ranged from eight to 40 miles from the earthquake epicenter. By comparison, the greatest building losses in the earthquake were in the area near the San Francisco-Oakland Bay

Bridge, which was more than 50 miles from the epicenter. In all, sixteen buildings were investigated during this survey, two of which were metal buildings.

Because the tomato season had recently ended in the Hollister area, almost all of the available warehouse-type buildings were filled with canned tomatoes. They were in palletized, one-gallon cans, typically stacked to a height of 20 feet or more. In a number of metal buildings, these unstable masses shifted during the earthquake and caused substantial damage to the building structures. It is important to note that even though some of the columns failed, there was no catastrophic failure that would have threatened human life. Also, the roof structures remained essentially in place and still provided a reliable amount of protection for the products stored in the building. This was not true of several concrete tilt-up wall buildings in the same area that failed and caused substantial roof collapse.

The survey team concluded:

> "metal building systems performed very well during this 7.1 magnitude earthquake. The only metal building systems that experienced any major problems were those that stored canned tomatoes. The failures experienced were due to this unstable stored material and were not a result of expected or required design loads. The building tenants and owners were very pleased with the performance of their buildings. The engineer of record should still pay particular attention to the connection design of metal building components when they are providing support for concrete tilt-up or masonry walls. The bracing systems of the metal building systems performed very well, even with heavily loaded mezzanines. Generally, no deformation of the brace rods or their connections was observed in this investigation. The wall panels of the metal building systems also performed very well, as did the primary and secondary structural members."

Northridge Earthquake (1994)

On Monday, January 17, 1994, at 4:31 a.m., an earthquake struck the community of Northridge, California. Northridge is in the central San Fernando Valley, north of Los Angeles. Although only a magnitude 6.6 on the Richter scale, the Northridge earthquake was a shallow-origin, thrust-fault seismological event that produced very high ground accelerations.

Engineers from the office of J. R. Miller and Associates made an independent observation of nine metal buildings in the San Fernando Valley. Their report stated, "in general, the metal buildings performed extremely well. In most cases, the buildings could be occupied as soon as utility service was restored." They went on to say, "in all the observed buildings, the bolted moment end plate connections appear to have behaved in a ductile manner and remained intact when subjected to the strong ground motion of the earthquake."

The only recommendation for improvement was to the detail of the tension-only rod brace connections where several localized failures were noted. The washers used with this connection, commonly referred to as hillside washers because of their sloped face, were susceptible to cracking because they lack ductility.

New MBMA Research Effort

So, why would the Metal Building Manufacturers Association (MBMA) feel the need to sponsor research on how metal building systems react to seismic loads if their performance record has been so good? The Northridge earthquake really shook things up in steel design, and metal buildings were caught up in the tsunami of proposed changes despite their exceptional performance record.

Conventional steel buildings, with their welded moment frames, were thought to be very ductile,- (i.e. able to endure significant deformations and absorb energy before failing). However, these structures suffered surprising cracks in the Northridge earthquake. Cracks were found in welds and connections where experts thought they would never exist in steel frames. However, as previously noted, bolted end-plate connections in metal buildings suffered no damage.

The research on steel frames and connection design after the Northridge earthquake was focused on multi-story frames, composed of prismatic, rolled shapes and welded moment connections. In fact, the Federal Emergency Management Agency (FEMA) 267 Interim Guidelines stated that "light, single-story, frame structures, the design of which is predominated by wind loads, have performed well in past earthquakes and may continue to be designed using conventional approaches, regardless of the seismic zone they are located in."

The primary steel frames in metal building systems are quite different from the prototype steel frames evaluated in the post-Northridge research. Metal building frames are optimized to match the envelope of maximum moment curves. Therefore, the frames are composed of welded plates that are commonly web tapered and may have unequal flanges. They are primarily single story, gable frames and are either clear span or utilize interior columns. In addition, the connections are bolted end-plates, not the field welded connections that posed problems in Northridge.

The current requirements for steel frames assume that deformation will occur at or near the beam-to-column connections. (This is called the plastic hinge location.) These requirements are also being enforced on metal building frames, in which preliminary analyses have shown that the plastic hinges will form at a considerable distance away from the column, due to the tapered member configuration. Therefore, metal building frames should be treated quite differently. Instead of focusing on whether the beam-to-column connection has the capacity to absorb this deformation, we should be concerned with other locations along the rafter beam.

We have adequate knowledge of how these frames perform elastically. This means we can be relatively confident that the structure will never reach the point where a plastic hinge would form. But to address the seismic design criteria, which are based on the premise that there will be some inelastic deformation, MBMA is sponsoring new research to evaluate the behavior of typical metal building frames beyond this point.

Conclusion

Metal buildings will continue to perform well in seismic events; but research is needed to determine how to ensure even greater performance. This will verify that metal buildings are efficient, yet not over-designed and wasteful of material. MBMA has taken a leadership role in this effort, first with the publication of the Seismic Design Guide for Metal Building Systems, and now with this important new research plan.

This new research, coupled with the observed performance of metal buildings, will enable the industry to move forward, positioned to be the construction-method–of-choice for low-rise buildings in areas of high seismicity. Stay tuned for updates on this research as we look to introduce changes into the codes and standards when the study is completed in the next two or three years.

Table 1: Major Earthquakes Investigated

Earthquake Location	Date	Richter Magnitude
Coalinga, CA	1983	6.5
Whittier, CA	1987	5.9
Loma Prieta, CA	1989	7.1
Northridge, CA	1994	6.6