Seismic Research: Metal Buildings are on Solid Ground

By W. Lee Shoemaker, Ph.D., PE

Which of these two historical dates; March 22, 1957 or January 17, 1994, was significant with respect to substantive changes in seismic design in the United States? The correct answer is January 17, 1994, when Northridge, Calif., was hit with a magnitude-6.6 earthquake. If you answered March 22, 1957, you get partial credit because that was when Elvis Presley's hit "All Shook Up" was released.

A 6.6-magnitude earthquake is not a monster temblor as earthquakes go. However, it was what seismologists call a shallow-origin thrust fault event that produced very high-ground accelerations. The seismic engineering community was surprised to find that some welded steel connections, typically used in mid- and high-rise buildings and thought to have excellent seismic resistance, were susceptible to cracking. Even though there were no catastrophic failures, an unprecedented federally sponsored research effort was launched to determine the cause of the cracks and to recommend new design practices. As a result, significant building code changes were eventually adopted that affected the seismic design of steel moment frames.

Metal building systems utilize steel moment frames in the transverse direction that are perpendicular to the ridge. However metal buildings utilize bolted end plate connections instead of the welded steel connections that were found to have the problem in Northridge. Despite this significant difference in connections, building code changes were sweeping and impacted all steel moment frames. Initially, the metal building industry was focused on adapting to the changes, and the Metal Building Manufacturers Association (MBMA) contributed with the development of a seismic design guide for metal buildings that was published by the International Code Council. This guide assisted engineers and plan checkers with applying the new seismic requirements to metal buildings.

However, as the new seismic design requirements and philosophical basis were better understood, the industry started to take a closer look at their applicability to metal buildings. This article will discuss the objective and status of this MBMA seismic research program that began in 2005 to address some of the post-Northridge code revisions and the associated limitations that were placed on light single-story frames.

Seismic Design of Buildings Using Steel Moment Frames

Modern seismic design focuses on providing sufficient ductility in a structure to absorb and dissipate the massive energy produced by an earthquake. Ductility is a measure of how much rotation, or drift, a building can tolerate before failure starts to occur. There are three steel moment frame systems currently defined and permitted in the building codes for resisting seismic lateral loads. Each has a different design rule that recognizes the amount of ductility that is anticipated, primarily based on the rotation expected at the beam-column connections.

The transverse steel moment frames used in metal building systems differ from the prototype steel frames evaluated in the post-Northridge research program. Metal building system frames are optimized to match the strength required at any location on the frame. Therefore, the frames are composed of welded plates that are commonly web tapered, with the web thickness and flange size selected to optimize material along the length. The members are more slender, with thinner flanges and webs than hot-rolled steel shapes that are typically used in multi-tiered conventional steel construction. Metal building systems are primarily single-story, gable frames and are either clear span or utilize interior columns.

All of the structural systems defined in the building code for carrying seismic lateral loads are assigned design rules. These rules, including the maximum building height permitted, depend on the seismic design category which includes the seismic hazard at that location and inherent ductility that each system embodies. One of the motivating factors for MBMA to initiate this research effort was the height limits imposed in high seismic areas. For example, the steel moment frames that are designed for the lowest ductility, called "ordinary moment frames," are not permitted in the higher seismic areas. However, there is an exception that was included specifically for metal buildings that permits buildings with lighter roofs and walls to be used to a height of 35 feet or 65 feet, depending on the weights and seismic risk. Metal buildings can comply in other ways, utilizing a structural system other than an ordinary moment frame that has higher height limits, but these are not always economic solutions.

Until recently, these design rules were based on engineering judgment and experience, but new rules refined after the Northridge earthquake require a rigorous analysis based on a sophisticated evaluation of the predicted collapse of a suite of buildings when subjected to predefined earthquake ground motions. This rigorous analysis is known as FEMA P695, based on the report and recommendation developed through the Federal Emergency Management Agency.

Early Research (Pushover Tests)

MBMA and industry partner American Iron and Steel Institute (AISI) jumped into seismic research by evaluating the behavior of full-scale metal building frames at the University of California, San Diego (UCSD) under the leadership of Dr. Chia-Ming Uang. This effort utilized load actuators to alternately push and pull a frame back and forth to assess the behavior and ductility of the system. (See Photo 1.) Many observations were made in this study, including how metal building moment

Photo 1: **Cyclic Test. One of the load actuators used to alternately push and pull the metal building system frame back and forth to assess its behavior and ductility.**

frames behave quite differently with regard to ductile design philosophy.

In fact, metal building frames demonstrated little conventional ductility. A hot-rolled shape in a multi-tiered moment frame exhibits ductility by forming a plastic hinge at the location of highest stress—typically in a beam near the connection to a column. However a more slender, built-up tapered member frame is governed by buckling of a flange or web, or a combination of both, before a conventional plastic hinge is achieved. Also, the location of the buckle is typically away from the column in a metal building gable frame.

This research led to a possible design strategy that was more appropriate for metal building frames. Instead of the ductile fuse concept, the design could be based on making sure the moment frame remains elastic during a design earthquake. That is, an appropriate factor of safety would be used to make sure the stresses are below a level that would cause any inelastic behavior or buckles. This design philosophy was feasible for typical metal buildings with lighter steel clad walls, but it would produce unreasonably heavier frames for metal buildings with mezzanines or heavier walls of concrete masonry or pre-cast tilt-up concrete where larger seismic forces are introduced due to their mass.

It is important to note that there are different approaches that would achieve the building code seismic performance objective, which is to prevent the collapse of a building during a design level earthquake. The buckled flange or web is not considered a failure in seismic design as long as overall stability is maintained, but it is an indicator of the beginning of inelastic behavior.

Shake Table Research

The next phase of the seismic research was undertaken to learn more about metal building performance by utilizing a full-scale shake table simulation. This is just as it sounds—a full-scale structure is erected on a base (table) that can be accelerated using large hydraulic rams programmed to shake exactly as the ground would during an actual

Photo 2: **Three specimens tested on the UCSD Shake Table.**

Metal building with metal sidewalls.

Metal building with heavy concrete walls.

Metal building with heavily loaded mezzanine and concrete sidewall.

earthquake. This testing was also conducted at UCSD on the largest outdoor shake table facility in the world, as part of a government-industry partner program. Three metal buildings were tested that incorporated metal sidewalls, heavy concrete walls, and a heavily loaded mezzanine on one-half of the building width plus a heavy concrete wall on the opposite side. (See Photo 2.) The roofs were loaded with steel plates to represent additional weight used in the seismic design of each building.

The tests were quite revealing. Shake table tests of this nature are intended to find out what magnitude earthquake is needed to collapse a building. As previously discussed, it is the collapse of the building that codes are trying to prevent. The maximum considered earthquake (MCE) for this collapse prevention requirement is a code defined earthquake for a specific site that is expected to occur once in approximately 2,500 years. The MCE applied to each of the three metal building specimens could not collapse any of them, even the ones with heavy mass walls and a heavily loaded mezzanine. The building with lighter metal walls actually withstood an earthquake that was twice the magnitude of the MCE without collapsing before the tests were suspended because the capacity of the shake table hydraulics was reached.

The shake table results were successful in demonstrating that the three metal building specimens were capable of satisfying the code performance requirement to remain standing during the MCE. As previously discussed, buckling would be permissible as long as stability was maintained. In fact, buckling was witnessed in the tests, which is the mechanism that dissipated the energy of the earthquake, as opposed to the formation of plastic hinges. (See Photo 3.)

Tapered Member Cyclic Tests

It was determined that more cyclic loading tests of tapered members was prudent since that was a key to how the frames buckled during the shake table tests. The better the understanding of how this buckling occurs under cyclic loading, the greater would be our confidence in the P695 evaluation and results. Therefore, a series of tests were performed at UCSD, subjecting a partial frame of tapered members to a cyclic load, to observe the buckling behavior.

Ten specimens were tested that included many construction details normally used in metal building systems, including flange splices, flange bolt holes, taper changes, holes in the web, etc. (See Photo 4.) It was found that the tapered members can undergo large cycles of loading of lateral torsional buckling without brittle failures and that common detailing found in metal buildings does not negatively impact their behavior. These results

Photo 3: Typical lateral torisonal buckles that formed on shake table tests to dissipate the energy of the simulated earthquakes.

Metal building with metal side walls.

Metal building with heavy concrete walls.

were useful in helping to calibrate the computer model that would be developed.

Computer Modeling of Shake Table Tests

The next step was to conduct computer simulations required by the FEMA P695 protocol. This involves hundreds of metal buildings that envelope the sizes and configurations of buildings anticipated and considers geographic locations that might have higher wind loads that could govern the design, etc. This is where one would include buildings of greater heights than the current limits to evaluate that important constraint. The computer simulations are based on our best understanding of the behavior of metal building frames, including what was learned during the shake table tests.

As previously mentioned, the P695 procedure determines the earthquake that can cause a collapse of the building being evaluated. Similar to the hydraulic limitations that prevented the collapse of the metal buildings on the shake table, modeling limitations prevented the UCSD researchers from collapsing a building in a computer simulation. This was because the model used in this P695 analysis was too simple to capture complex behavior associated with various forms of buckling and inelastic behavior. In other words, we need a better analysis model that can go far beyond any existing model used in the evaluation of currently recognized seismic systems. This was known at the outset, but it was the only practical tool available. "Collapse" was restricted to and defined as the initiation of buckling, i.e., flange local buckling, web local buckling or lateral torsional buckling.

Photo 4: One of the series of tests performed at UCSD, subjecting a partial frame of tapered members to a cyclic load, to observe the buckling behavior.

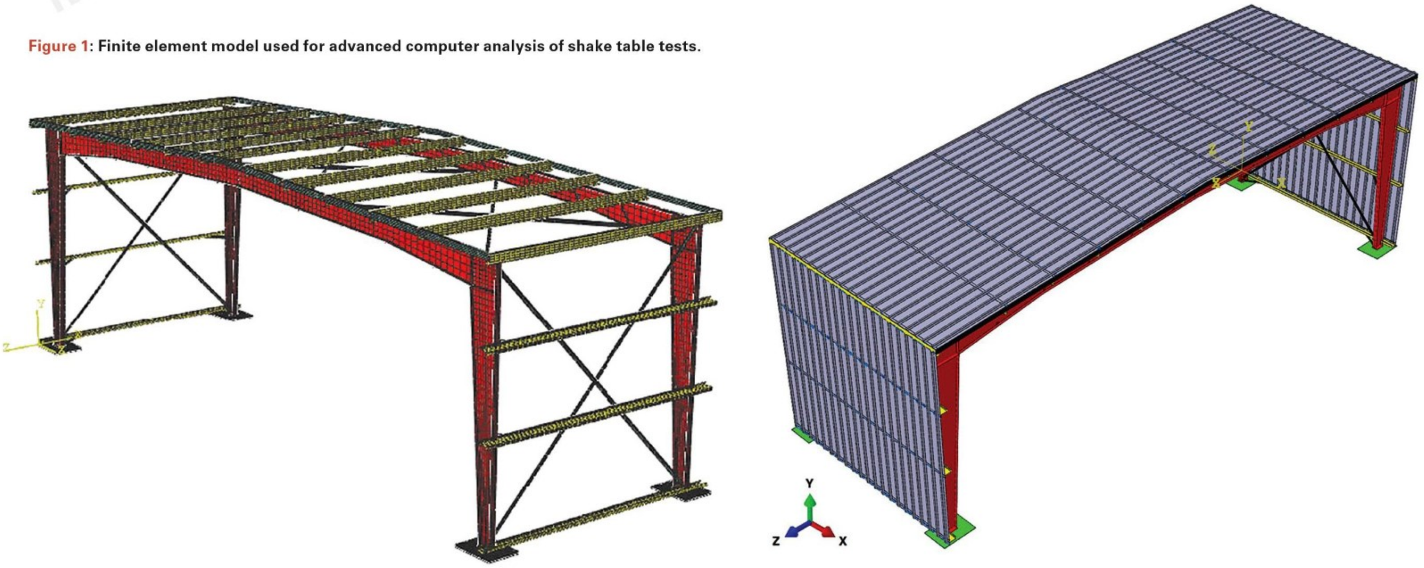
These modeling limitations would produce seismic design rules that were overly conservative and not consistent with the P695 protocol based on real collapse. The P695 studies were put on hold until more sophisticated modeling capabilities could be developed.

Advanced Computer Modeling

It became obvious that more sophisticated computer models would need to be developed to be able to come closer to predicting the actual collapse of a metal building for a more advanced P695 evaluation. This would have to include the ability to predict the inelastic behavior, i.e., nonlinear behavior beyond the first buckle. We know that the metal building frames continue to carry increasing load after the first buckle appears based on the shake table tests, so we have to be able to accurately capture that in a computer simulation.

Dr. Ben Schafer and Dr. Cris Moen at Johns Hopkins and Virginia Tech University respectively, are leading the effort to develop the most sophisticated computer model ever attempted of a metal building. They are utilizing advanced finite element modeling to represent every piece of a metal building. This essentially means representing every

Figure 1: Finite element model used for advanced computer analysis of shake table tests.



Model shown with structural framing.

Model shown with roof and wall sheeting.

member, brace, sheeting, bolt, etc. by a mathematical element. (See Figure 1.) These elements are defined with respect to their material properties as well as their structural behavior at a basic level. Then, they are all tied together with the appropriate glue and springs, or boundary conditions. The mass of all of the elements is also included so that when accelerations are imposed on the model to represent actual ground motions, the forces are generated just as they would be in an actual earthquake. Inelastic properties are included so that when a flange starts to buckle, the model is automatically updated to reflect the accompanying change in geometry and stiffness. The analysis then proceeds in an incremental fashion.

Other modeling considerations include initial imperfections and residual stresses. Initial imperfections need to be built into the model that reflect the fact that all members are not fabricated perfectly or erected perfectly. Conventional design assumes imperfections and that is built into the design equations. However, finite element modeling has to directly address imperfections and build reasonable assumptions into the model. Residual stresses are stresses that are locked into members as a result of steel production process, welding or other constraints and need to be included in the overall evaluation of stresses in the members. Welds are also directly modeled as elements connecting flanges to webs, etc.

The generation of all of the finite elements in a model of this fidelity—defining the properties and the location of every element in the model, could be a monumental task. Keep in mind that a single purlin might be defined by hundreds of elements representing the web, flanges and lips segmented along the length. (See Figure 2.) The researchers have developed a way to automatically generate all of the elements by inputting material information and basic geometric layout of the building and members. This will be necessary as the P695 moves forward and hundreds of building models will need to be generated and evaluated.

The intent of the finite element models will not be to simulate collapse of the buildings, but to closely match the exact behavior of the metal buildings on the shake table, up through the maximum considered earthquake.

Figure 2: Part of the finite element model showing detail of modeling required to capture the complex inelastic behavior of a metal building system.

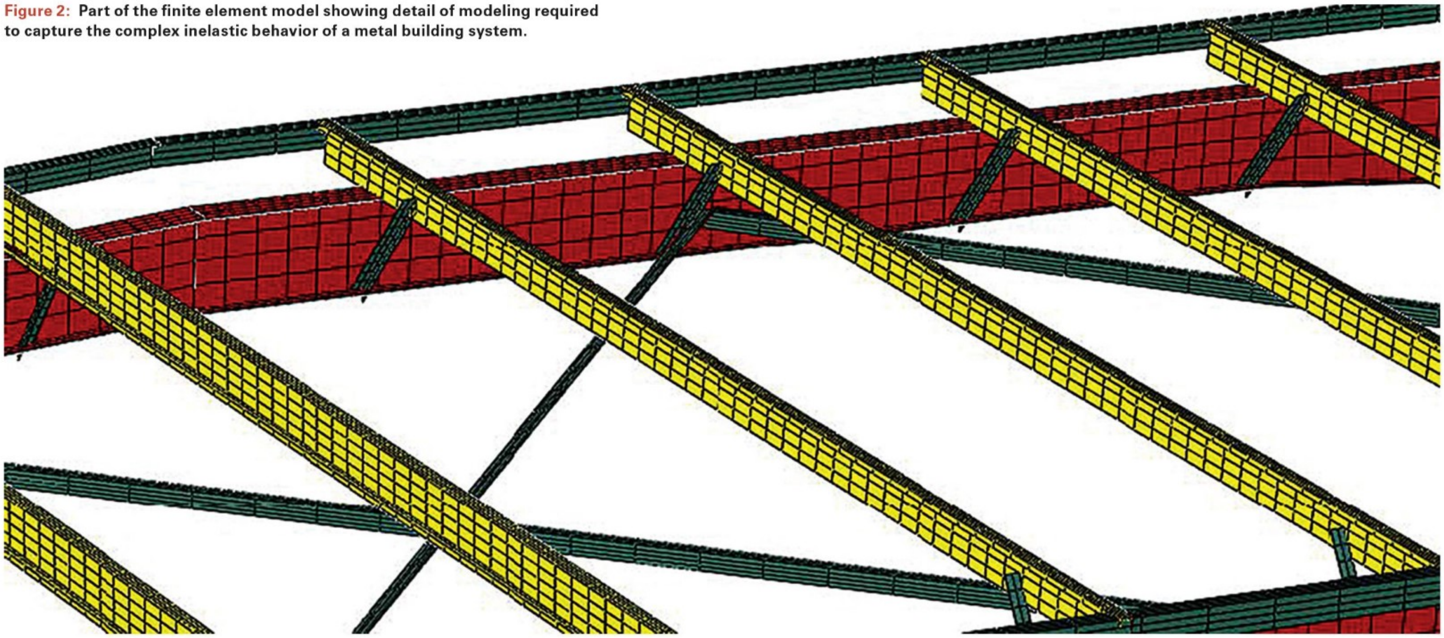
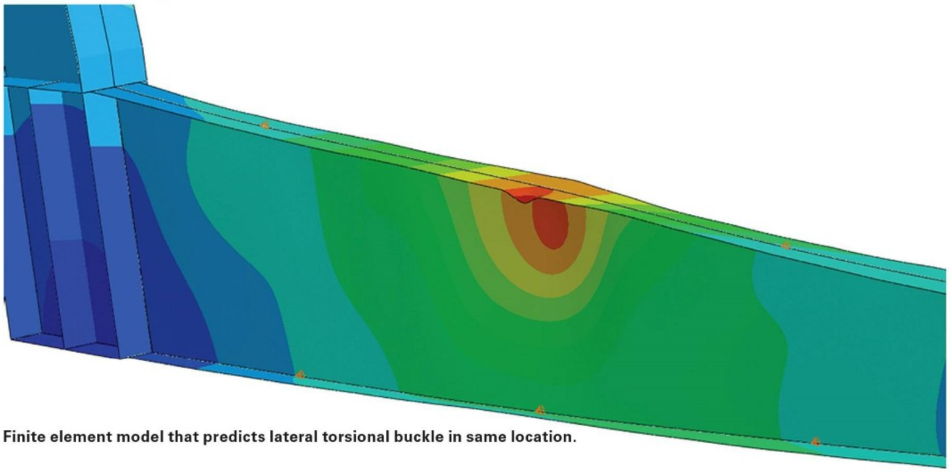


Photo 5: **Comparison of actual test showing lateral torsional buckle and finite element model of same test.**

Test of rafter showing the formation of lateral torsional buckle.



Finite element model that predicts lateral torsional buckle in same location.

Modeling Progress

The finite element modeling has made great strides over the past 12 months. The automatic generators are simplifying the process of building the models. The first step in validating the finite element models was to try to replicate the cyclic test results of the tapered member frame sections. This verified that the model is capturing the nonlinear inelastic behavior of the tapered frame members with slender flanges and webs, which is essential to representing the entire moment frame action. (See Photo 5.)

The next step in validating the model was to try to simulate the first shake table test of a metal building with light metal walls. This involves a dynamic analysis, where the finite element model is in motion, matching the deflections and accelerations imposed on the building by the shake table. The model did an excellent job in replicating the behavior of the actual building subjected to earthquake ground motion.

Work is almost complete on the verification of the model to the second shake table building that had heavy concrete tilt-up walls. Finally, the third shake table building will be modeled to complete the verification process. The third building is unique with respect to the energy dissipation mechanism. Instead of a flange or lateral torsional buckle, the panel zone at the connection of the rafter to the column exhibited flexing and buckling. It will be important to demonstrate that the finite element model correlates well with this different type of initial failure.

Summary

The purpose of this major seismic research effort is to develop the appropriate design rules for a typical metal building that uses tapered frame members. This would include the appropriate height limitations based on the buildings evaluated to develop the rules, keeping in mind that no height limit might be appropriate for certain metal buildings in high seismic areas.

The shake table tests completed at UCSD provided invaluable data and observations on the actual behavior of three distinctly different metal buildings. The buildings performed exceptionally well, exceeding everyone's expectations.

However, the task at hand is to develop a sophisticated computer model that can reproduce the behavior of those three shake table tests. The building code and standards bodies require that a suite of metal buildings called archetypes, representing all of the important parameters that would affect seismic behavior, be evaluated using FEMA P695. Design assumptions will be made to develop the metal building archetypes that will then be modeled. The computer models will be subjected to a predefined series of ground motions to see if they collapse. The procedure is iterative, whereby a collapse would result in changes to the design rules and the process would be repeated.

MBMA and AISI are supporting this research effort, which was initiated in 2005. We have had excellent researchers working with us on this journey. The completion of the P695 study and development of the design rules is the aim of the research, but it is only the beginning in terms of gaining acceptance and approval in the codes and standards. That process is assisted by including a peer review panel in the process. We have been fortunate to have top academics and consultants serve on our peer review panel, and provide review and guidance. (See Sidebar.)

The fruits of this research will not only address the immediate need to develop appropriate seismic design rules for metal buildings, but will advance the state-of-the-art advanced finite element modeling for our industry. One day, as computer power continues to evolve, advanced models may bridge the gap between research and everyday design tools to take advantage of the inelastic reserve strength that we now know is available and can quantify.

W. Lee Shoemaker, Ph.D., PE, is the director of research and engineering for the Metal Building Manufacturers Association, a position he has held for more than 20 years. He is responsible for the development and administration of the metal building industry's research programs. To learn more, visit **www.mbma.com**.

Five academics and consultants have served as a peer review panel for P695 study being undertaken by MBMA and AISI. They are:

Dr. Michael Engelhardt, University of Texas

Dr. Greg Deierlein, Stanford University

Dr. Tom Sabol, UCLA and Englelkirk & Sabol Consulting Structural Engineers, Los Angeles

Dr. Don White, Georgia Tech University

Mark Saunders, Rutherford + Chekene Consulting Engineers, San Francisco