Structural Performance

performance issues relative to extreme events

ife safety has always been a fundamental goal of U.S. building codes. With the introduction of the International Building Codes (IBC) in 2000, new demands have been placed on engineers, manufacturers and builders who produce structures in earthquake-prone regions. Prior to the IBC, engineers were accustomed to designing buildings to prevent damage such as buckling and yielding. Today, the challenge is to better understand what happens after buckling and yielding, up to and including collapse. Life safety through the avoidance of earthquake-induced collapse is the approach today's engineers must take to accomplish the intent of the code for structures in areas with high seismic activity. This change in design objective spurred much needed research and testing in the industry.

There are numerous ways to determine when a building will reach collapse. The most advanced of these are complex, lengthy and ill-suited for use

behavior when considering collapse for common

systems made of concrete, masonry, steel and

wood structures. Since 2000, Metal Building

Manufacturers Association (MBMA) has been

working to extend the knowledge base contained

in the code by researching the particular phenom-

enological, or characteristic, behaviors (such as

buckling and yielding) of moment frames with

tapered members subject to earthquake-induced

in a production design setting. Fortunately, the IBC code writers had the foresight to include a simplified method for production settings that approximates building shaking. The objective has been to quantify how tapered member frames behave after buckling and yielding, and then to confirm or develop new factors and limits for design.

Framing the Situation

Moment frames make up a key force-resisting system in any building. For decades, MBMA and its member companies have been designing buildings with moment frames containing tapered members with the objective of precluding yielding and buckling within a margin of safety. Today, most companies design for seismic demands using the simplified method contained in the IBC. Seismic performance factors (SPFs) in building design are simplified and approximate methods of accounting for post-peak behavior exhibited when buildings are subject to strong earthquake shaking. Post-peak behavior occurs after buckling and yielding, but before collapse. More advanced methods of analysis include inelastic pushover and inelastic dynamic analysis methods that consider post-peak behavior, and then set an adequate margin of safety against collapse. The FEMA P695 document illustrates a detailed analysis method used to generate seismic performance factors for simplified design.

Steel ordinary moment frames (OMF) are used by the industry where allowed by the code. Steel OMF SPFs have been used to address a wide range of building configurations. Steel OMFs, in general, are expected to exhibit limited ductile behavior and, therefore, have limits placed on design. For example, steel OMFs in Seismic Design Category D are limited to building heights up to 65 feet with a roof dead load that does not exceed 20 psf and a wall dead load does not exceed 20 psf above 35 feet.



A 60-foot wide steel building tested during the MBMA and AISI sponsored Moment Frame Seismic Study at the University of California San Diego in Spring 2011. The study included three frames placed on the largest shake table in the U.S. to better understand how metal buildings behave when subject to earthquake loading.

Modern Construction: Standing Solid on Shaky Ground

New Advances in Design and Testing for Seismic Demands

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Ductility is important in building materials because it allows dissipation of the energy introduced by an earthquake through damage to the structure. It changes the physical behavior of the structure, thereby reducing the damaging effects of the shaking. Said another way, ductility is the ability of an element to sustain large amounts of damage prior to developing degrading behavior. Ductile behavior is not only important in preserving life safety but also in producing economical buildings.

Researchers and engineers in the metal building industry have long felt that better differentiation was needed in the simplified method to characterize building types produced by MBMA. The MBMA has been working to fully understand the post-peak behavior exhibited by the frames produced. Therefore, the industry is using detailed testing and analysis to develop appropriate SPFs and limits for tapered member moment frames for a range of applications.

Understanding Behavior

MBMA, under the guidance of Lee Shoemaker, Ph.D., P.E., F.SEI, MBMA's director of research and engineering, has been working to better understand the phenomenological behaviors of metal building components which have contributed to metal buildings' faring well in recent major California earthquakes, like those in Loma Prieta in 1989 and Northridge in 1994. The low level of damage experienced by metal buildings in those seismic events can be attributed - in large part - to their low rise and lightweight. MBMA does produce structures with heavier loads such as buildings with tiltwalls and mezzanines. For these structures, seismic loads have a large influence on design.

A multi-year research program is now underway to help researchers and engineers understand why metal buildings perform so well, and to take full advantage of the benefits of these structures. To better understand ductility in metal buildings, MBMA initially sponsored full-scale push over and shake table tests at The University of California at San Diego (UCSD). Chia-Ming Uang, Ph.D., and graduate student Matt Smith, performed initial research on tapered member frames. These tests determined that low-rise buildings with metal roofs and wall panels exhibit a large degree of over-strength for seismic loads.

In addition to metal buildings with roof and wall metal panels, shake table tests were also performed on a frame with tilt-wall panels and a frame with a mezzanine. During the test, lateral-torsional buckling (LTB) followed

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A close-up of the panel zone, showing buckling sustained during the shake table testing at the University of California San Diego in Spring 2011. The building actually survived 300 percent of its design load.

by flange rupture was observed in the rafters of these frames, along with damage found in the panel zone and at the column base plates. The most ductility in the frames tested was attributed to the dissipation of energy in the panel zone. The LTB of frame rafters allowed redistribution of lateral load to a more stable configuration. These initial frame tests will provide data for future studies and ideas.

Redistribution of load was another interesting observation resulting from the shake table tests. Once LTB occurred in a rafter of single span frames, the load on the frame was redistributed. Smith noticed the single span frame behaved like a three-pinned arch after LTB, which is a stable configuration. With load applied to the right side, the right rafter developed LTB. When the load was reversed, the LTB in the right rafter straightened out and LTB occurred in the left rafter. Again, the result was a stable three-pinned arch. The different unbraced lengths at the top and bottom flanges of the rafter made this possible. The extent of this behavior has yet to be determined, but doing so will help to predict behavior all the way to collapse.

Based on observations during the shake table tests, it was concluded that rafter LTB would be useful in evaluation of when a building will collapse. The decision was made for UCSD to perform 10 rafter component tests in order to gather the data to calibrate rafter LTB postpeak behavior models, which will be useful in the more advanced analyses.

Through the shake table tests, unanticipated rafter vertical behavior was observed. The code currently requires a uniform vertical load be applied to frame design, which approximates the vertical motions of an earthquake. Based on the observations of the shake table test results, it may also be appropriate to use a patterned vertical load to reflect wide span rafter behavior subject to lateral loads.

Smith also developed a fundamental period equation that approximates low-rise building behavior more closely than the approximate options currently contained in the codes for all building heights.

Solutions for the Future

A major goal of the metal building industry is to numerically define the behavior and ductility available in the frame components. MBMA, through their research efforts, has gathered data to model LTB in rafters. These data provide some of the building blocks for the detailing, design and construction of tapered members intended to preclude collapse under code prescribed seismic loading. Focuses of current studies were determined from observations of the shake table testing of three full-scale single span buildings.

Modeling for the panel zone, beam-tocolumn connections and column bases still needs to be addressed. Data collected from the shake table testing was used to create models that characterize panel-zone behavior in the test frames, but it needs to be extended to accommodate all the panel-zone geometries produced by MBMA member companies. Connection modeling is well under way. The metal building industry has been studying bolted beam-to-column connections for the past 40 years. Tom Murray, Ph.D., P.E., professor emeritus at Virginia Tech, and others have provided multiple research papers describing bolted connections subject to static and dynamic loading. This connection research contributed to the development of the AISC Steel Design Guides No. 4 and No. 16. Work is underway at Virginia Tech by Matt Eatherton, Ph.D., and Murray to expand the applicable configurations addressed in Design Guide No. 16.

Tapered rafters attached to columns tend to move the location of first damage (LTB) away from the column. Due to this behavior, the industry feels that AISC *Design Guide No. 16* connections are adequate for tapered member rafters since the first damage is not adjacent to the connection. The connections used in the shake table testing were designed using the AISC *Design Guide No. 16* and performed well when load was applied.

Many distinguished researchers have studied column base modeling, including Bora Gencturk, Ph.D., at the University of Houston. He is working to understand the level of stiffness available in column bases accessible to the engineer in production design of metal buildings and to observe post-peak behavior of these elements. He is also researching the pinned assumption, or when the connection is free to rotate but not free to translate, and at what point it no longer adequately models actual frame behavior in the column base configuration. For metal building frames, it is a conservative assumption that the column base is pinned, especially when estimating building drift. The implications on the foundation are of more concern.

Putting the Pieces Together

Once post-peak models of appropriate elements are generated, FEMA P695 modeling can begin. The benefit of this analysis comes from quantifying the post-peak behavior of appropriate elements. Shoemaker assembled a peer committee to oversee efforts to perform a P695 analysis. The peer committee, composed of Greg Deierlein of Stanford University, Tom Sabol of Englekirk and Sabol, Mark Saunders of Rutherford & Chekene and Mike Engelhardt of The University of Texas, attended the UCSD shake table testing to provide insights and recommendations.

The task of P695 modeling is not isolated to one building or one type of building. The range of products offered by MBMA member companies is large and several different groups of SPFs will need to be better understood, including the following types of buildings: single span, multi span with light metal panel wall, walls clad with tiltpanels, brick, and masonry. Heavy roof loads or crane loading, along with buildings with mezzanines, are also on the agenda to be investigated. Once MBMA has obtained numerical modeling of appropriate components, the effort of inelastic pushover and dynamic analysis begins. Only then will researchers truly understand the ways different buildings behave up to and including collapse.

It is important for engineers to understand that the limits placed on systems in the building code as part of the simplified procedure were placed there for a reason. It was the judgment of the experienced engineers who wrote the limits, and designing beyond them should only be done through the P695 methods of analysis. MBMA is closer than ever before to understanding how tapered member frames behave up to and including collapse. Accomplishing this goal will give the industry more flexibility in design with appropriate limits set on these systems.