STRUCTURE

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MARCH 2025

Resilience & Mast Frames

Rendering of Samuel Merrit University's new campus headquarters in Oakland, California (Courtesy of Perkins & Will).

Improved Economy & Resilience With Mast Frames

An innovative seismic design approach provided an optimal solution for Samuel Merritt University's new steel 10-story, 259,000-square foot research, and academic building.

By Jason Armes, SE; Gina Carlson, SE; and Leo Panian, SE

The challenges of selecting the appropriate seismic system involve the trade-offs and compromises between architectural design, space planning, construction cost, and seismic performance. For Samuel Merritt University's (SMU) new high-rise research, and academic building in downtown Oakland, California, an iterative design approach resulted in a novel and cost-effective structural system that provides an unobstructed floor plan and superior seismic performance.

Working closely with the developer, contractor, and architect team, Tipping, as the structural engineering team, investigated different design strategies, including moment frames, dual systems, conventional Buckling Restrained Braced (BRB) frames, and Buckling Restrained Mast-Frames (BRBM) to develop the most effective approach. This allowed the team to make detailed comparisons of

Project Team

Structural Engineer: TippingArchitect: Perkins&Will
Owner: Samuel Merritt University
Developer: Strada Investment Group
Contractor: Hathaway-Dinwiddie Construction Company
Steel Fabricator: The Herrick Corporation
BRB Supplier: CoreBrace

architectural impact, material use, and seismic performance to arrive at the preferred solution.

The system ultimately selected is a variation of the conventional BRB frame, which incorporates a vertical mast or strongback element. This configuration, referred to as a Buckling Restrained Braced Mast (BRBM) frame, effectively separates the elastic and energy dissipating components of the system resulting in a more resilient and reliable structure. The mast element consists of a vertical truss that is designed to stay elastic and work in conjunction with BRB devices, which yield and dissipate seismic energy.

The BRBM system has been used in previous projects, but the SMU example is the largest and tallest application of the innovative system. The compact footprint of the BRBM frames allowed them to be largely concealed within permanent demising walls. Their inherent redundancy allowed for fewer frames in the building and significantly reduced the number of BRB devices, both minimizing the impact to interior spaces and resulting in overall cost savings.

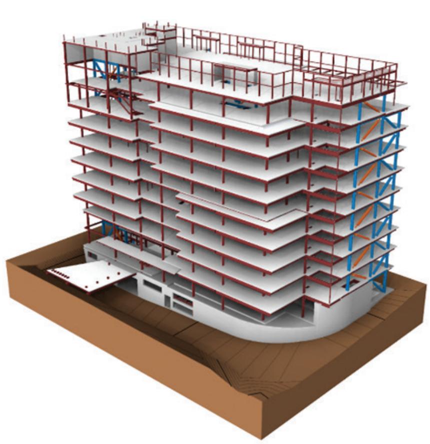

Photo courtesy Remote Optix

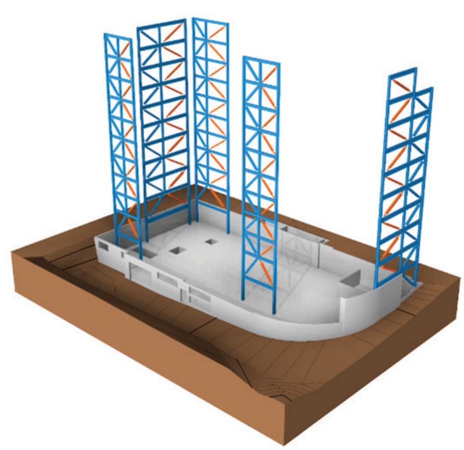
Case Study

The new high-rise building will serve as the flagship campus for Samuel Merritt University. The nursing and health science education

Structural System Summary

- **Plan Dimensions:** 218 feet by 115 feet
- **Height:** 146 feet to roof, with 23-foot deep basement
- **Bay Spacing:** 23 to 42 feet
- **Floor Assembly:** 6¼-inch lightweight concrete slab over metal decking on wide-flange beams and columns
- **Seismic Load Resisting System:** Buckling restrained braced frames with mast elements
- **Foundation:** Mat slab supported on unimproved soil





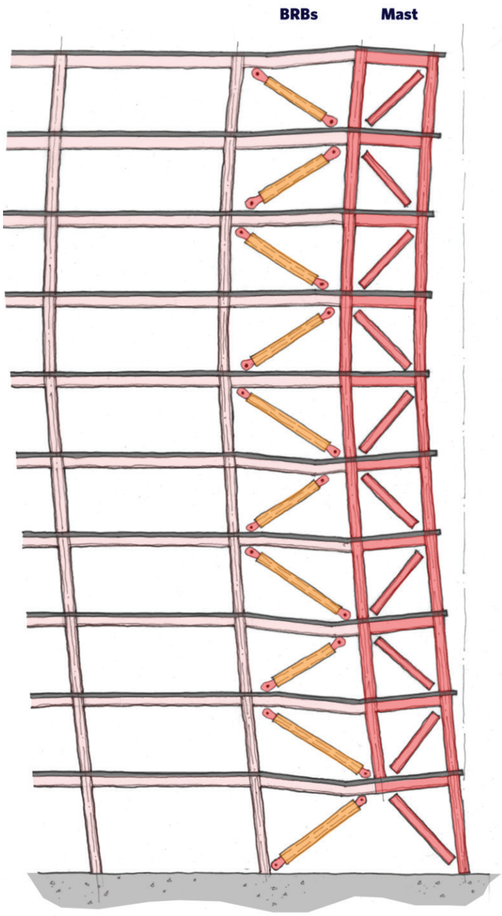
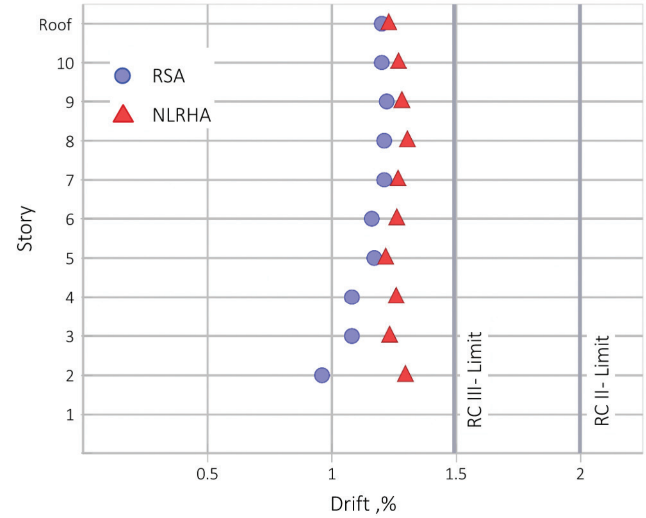
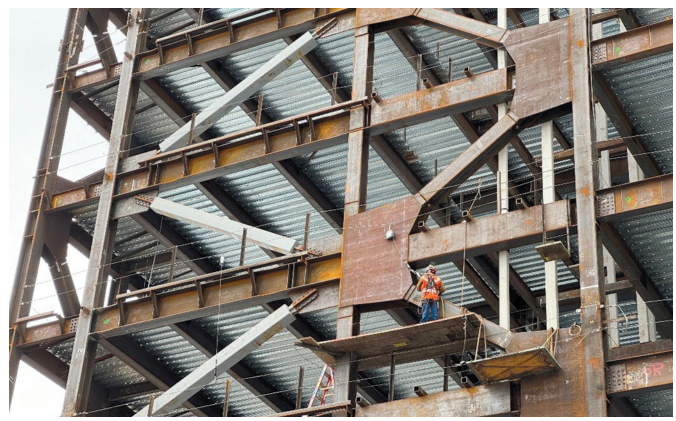


Illustration shows inelastic mechanism of BRBM frame, with yielding BRBs on the left half working in tandem with an elastic mast on the right. The mast truss incorporates W14x665 columns and W14x233 diagonals and is capacity-designed to protect against overload.



Estimated maximum drifts for the design basis earthquake (DBE), comparing response spectrum analysis (RSA) and non-linear response history analysis (NLRHA), with limits for Risk Categories (RC) II and III.



Construction of BRBM frame showing uniform member sizes and connections.

facility, which is slated to open in 2026, will feature classrooms, laboratories, clinics, offices, and community gathering spaces. Though the building is located on a dense urban site, setbacks from neighboring buildings allow for a large majority of the facade to consist of a glazed curtainwall providing views and access to natural light. An offset vertical circulation core allowed for large unobstructed classrooms and flexibility for lab planning.

Initial Design Concepts With Moment Frames & Dual Systems

During the conceptual design phase, Tipping initially investigated a moment frame system to ensure that the variety of uses could be flexibly accommodated. Frame member sizes were governed by seismic deflection criteria and were proportioned to limit the maximum inter-story drift to 2.0%. The resulting system required numerous frame lines with deep beams, heavy columns and intersecting columns with custom shapes. It also came with a significant cost premium due to the relatively high quantity of steel required, estimated at 9 pounds per square foot of floor area. Due to its inherent flexibility and increased propensity for damage, the moment-frame system provided the least resilient approach.

Key advantages of the BRBM system include its ability to maintain an open floor plan and maximize facade transparency while significantly improving seismic performance.

The structural design team also evaluated a dual system, which combined BRB frames in each direction to supplement the moment frames. The intent was to leverage the stiffness of the limited number of brace frames to limit drift and reduce the overall quantity of steel. Due to incompatibilities in stiffness between the moment frames and braced frames, effective load-sharing between them was difficult to achieve. This dual system would still rely on heavy moment frames to resist a minimum of 25% of the total seismic load, as required by the ASCE 7 code. With the addition of 40 BRBs, the dual system resulted in a slight reduction of overall steel quantity, with estimated total of 8.7 pounds per square foot of floor area, and a modest improvement in performance, with an estimated inter-story drift of 1.85%. While the dual system was an improvement over the moment-frames alone, it provided only limited gains in performance or economy.

Buckling Restrained Brace (BRB) System

In further exploring potential design solutions, the design team investigated concentrically braced frames relying entirely on BRBs. Due to the limited number of frame bays that were available to locate diagonal braces, the system needed to be designed for a 30% increase in lateral loads to account for the lack of redundancy of the system. This led to heavy, built-up column sections and very large BRB members, particularly at the lower stories, where the lateral loads were the highest.

Despite the redundancy penalty, the BRB frame system offered a significant improvement in terms of cost, performance, and impact to the architectural design. This approach resulted in a significantly reduced quantity of steel for the lateral load resting system, estimated at 3.2 pounds per square foot of floor area. The system incorporated a total of 100 BRB devices and resulted in a significantly reduced maximum inter-story drift of 1.70%.

While this represented a reasonable and cost-effective solution that met the basic design goals, there was an opportunity to further improve the seismic resilience of the building. Our analysis showed that despite the fact that seismic drift was well below the code limit, the BRB devices were only partially mobilized to resist seismic shaking. The team observed that most of the lateral deformation and damage tends to concentrate at individual stories and components rather than being more evenly distributed, significantly limiting overall seismic resilience.

Mast frame construction with facade and fire proofing partially installed.

BRB Mast System

To mitigate these shortcomings and develop a more optimal scheme, the design team investigated a system that incorporates a vertical mast or strongback within the braced frame to augment the BRBs. This variation of the conventional BRB frame effectively separates the elastic and energy dissipating components of the system to better control structural response and improve seismic performance. This approach relies on a full-height truss, made of conventional wide-flange sections, that works in conjunction with the yielding BRB devices to improve the redundancy and performance of the system. The rigidity and strength of the mast significantly reduces the maximum expected seismic drift and ensures a more uniform drift distribution throughout the height of the building. This effectively eliminates story mechanisms and localization of damage resulting in a more resilient and reliable structure.

By interconnecting all of the BRB devices throughout the height of each frame, they are fully utilized and capable of sharing loads between stories. This effectively improves the redundancy of the system and eliminates the 30% penalty, leading to increased efficiency.

These advantages can be gained with minimal or no cost premium over a conventional BRB-only frame system. Ultimately, this approach resulted in an estimated steel quantity of 480 tons or 3.7 pounds per square foot of floor area for the lateral load resisting system. This represents a slight increase from the conventional BRB-only system, owing largely to the incorporation of the vertical truss that serves as the mast. However, this system used only 50 BRB devices, making up the cost of the additional steel quantity.

The maximum drift for the BRBM system under the design basis earthquake (DBE) was estimated to be 1.20% using a Response Spectrum Analysis (RSA) and 1.30% using a Non-linear Response History Analysis (NLRHA). The ratio of maximum-to-average drift over the height of the building was 1.09, indicating a relatively uniform drift profile with no concentration of story deformations. This level of performance is a significant improvement over conventional practice that can provide measurable gains in seismic resilience.

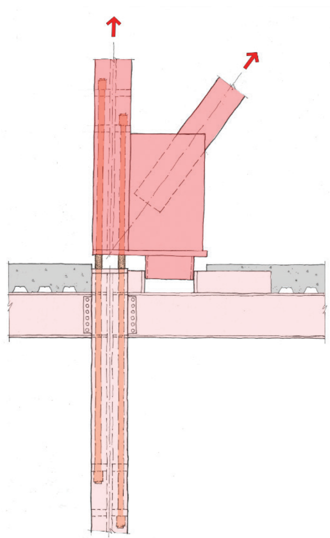


Illustration of BRBM base connection that uses a shear lug to transfer horizontal forces and four 10-foot long, 2.5-inch diameter, high-strength rods to resist overturning tension forces, while allowing rotational flexibility.

The BRB mast frame system was designed using the prescriptive procedures outlined in Chapter 12 of ASCE 7-16 and the AISC Seismic Provisions for BRB frames described in Chapter 5.5, using an R-value of 8. The design method was adapted for the treatment of the mast truss and extensively validated using non-linear static and dynamic analyses.

Each frame-bay incorporates a mast truss on one side and a single BRB device on the other. The mast side is typically proportioned to be slightly narrower than the BRB-side, making the devices more efficient in resisting horizontal loads and longer allowing increased deformation capacity. Under elastic load levels, the mast truss resists roughly 40% of the total base shear. Because the truss is designed to remain elastic under all loading conditions, it can make all of the BRB devices in the frame to share the total load. This allows the BRBs to be more uniformly sized throughout the height rather than becoming increasingly larger towards the base, simplifying detailing and avoiding extreme proportions.

To ensure that the system performs as intended, the mast members were proportioned using capacity-design principles, an approach that is analogous to the design of columns in the frames. Once the BRB sizes were determined using a preliminary response spectrum analysis and optimized for a more uniform distribution of forces, the forces in the mast truss were amplified to reflect the maximum anticipated loads that could be delivered by the yielding BRBs. Initially this consisted of applying an overstrength factor of 2.5 to estimate the required demands on mast members. This approach was reasonably effective for estimating the maximum loads on the mast truss. To validate this critical assumption, we deployed non-linear analyses to capture the inelastic response of the system and refine the design of the mast members and BRBs.

To allow the mast frames to rock and pivot more freely about its base and prevent overstressing the gravity support columns, the design team developed an improvised pin connection that could resist large shear and overturning axial forces while allowing rotation. The detail relied on direct steel-to-steel contact at the base connections to deliver axial compression and shear. To transfer tension forces, Tipping called for long high-strength rods to anchor the base of the mast.

The design was submitted for plan review and approved through a conventional permitting process, which did not require a special Alternate Materials and Methods Request or formal peer review.

Conclusions and Take-aways

The implementation of BRBM frames represents a significant advancement in the seismic design of steel structures, particularly for high-rise applications like Samuel Merritt University's flagship campus. Through an iterative design process that evaluated various structural systems, including moment frames, dual systems, and conventional BRB frames, the BRBM system emerged as the optimal solution, balancing cost-effectiveness, architectural flexibility, and seismic resilience.

Key advantages of the BRBM system include its ability to maintain an open floor plan and maximize facade transparency while significantly improving seismic performance. By integrating a vertical mast truss with BRB devices, the system minimizes story drift, eliminates damage concentrations, and enhances system reliability, resulting in improved structural response during earthquakes. This innovative approach also reduces the overall number of BRB devices and avoids excessive column and beam sizes, addressing common architectural and economic challenges associated with traditional systems.

The design process underscores the importance of tailoring structural solutions to project-specific needs and site constraints. The use of advanced analytical techniques, such as non-linear static and dynamic analyses, further validated the BRBM system's capacity to meet stringent safety, serviceability, and resilience requirements. This achievement not only sets a precedent for future seismic designs but also highlights the potential of collaborative engineering to drive innovation. ▪

Leo Panian is a Principal with Tipping and served as the Structural Engineer of Record for the project. Gina Carlson is an Associate Principal with Tipping and served as the Project Director. Jason Armes is an Associate with Tipping and served as the Project Manager and Technical Lead.