Design for Speed & Resiliency

A steel moment frame structure case study merges a modular biaxial steel special moment frame system and a prescriptive damped frame design method.

By Matthew Bosch-Willett and Nathan Canney

Design in accordance with modern seismic codes is intended to achieve certain performance objectives depending on Risk Category (RC) and hazard severity. For example, a typical RC II structure (e.g., an office building) is expected to achieve life safety performance for the design earthquake (DE) event and collapse prevention at the maximum considered earthquake (MCE) (Table 1). The expectation for the life safety performance is that occupants remain safe during the earthquake but need to evacuate afterwards. In contrast, an RC IV structure (e.g., a hospital) is expected to achieve an Immediate Occupancy performance level at the DE earthquake, meaning that occupants remain safe and the facility retains most operations immediately afterwards.

Achieving life safety, however, does not guarantee a community can recover quickly from severe events or return to normal operation. Modern society needs structures that are built quickly and have minimal downtime following a major seismic event. Combining the ConXtech ConXL400 modular biaxial structural steel special moment frame (SMF) system with fluid viscous dampers is one way to achieve this goal.

Modular Biaxial Steel Special Moment Frame

The steel SMF in this study is a chassis-based modular system wherein modularity is implemented at the connections between members. The centerpiece is a wrap-around collar assembly, a one-size-fits-all bolted prequalified SMF connection that joins wide-flange beams to concrete-filled composite 16-inch square Hollow Structural Section or built-up box columns. The collar is a biaxial moment connection allowing the same column to participate in orthogonal moment frames (Fig. 1).

With collars distributed throughout the floor plate, the system engages more members in the lateral force resisting system (LFRS) than conventional designs, enhancing redundancy.

Dampers

Fluid viscous dampers (FVDs) are velocity-dependent energy dissipation devices. FVDs are governed by the constitutive equation $F = CV^{\alpha}$, where F is the output force, C is the damping constant, V is the velocity, and alpha is the velocity exponent. Forcing a machined piston head through a viscous fluid is how FVDs convert kinetic energy into heat energy, reducing story drifts, accelerations, and yielding in the LFRS. All these benefits lead to more resilient buildings while reducing building material quantities.

The Taylor damped moment frame (TDMF) is an ICC-approved alternative LFRS which utilizes SMFs and supplemental damping with FVDs. Developed and validated through the ICC AC494 and FEMA P-695 procedures, buildings designed in alignment with this procedure meet the code-intended collapse probabilities (i.e., 10% at MCE_R for RC II) and can be used per ASCE 7-22 Section 12.2.1.1. This prescriptive approach relies solely on modal response spectrum analysis (MRSA) rather than nonlinear analysis per ASCE 7 Chapter 18.

Table 1. Expected Performance Versus Risk & Ground Motion Severity

Risk Category	Ground Motion	Performance Level
RC II	Design	Life Safety
	MCE	Collapse Prevention
RC IV	Design	Immediate Occupancy
	MCE	Life Safety

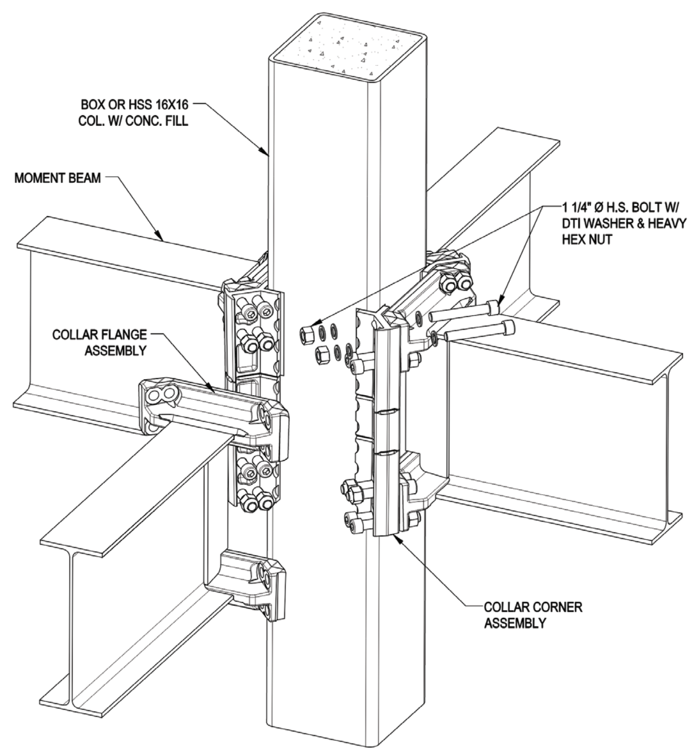

Fig. 1. The bolted modular biaxial SMF collar connection allows the same column to participate in orthogonal moment frames.

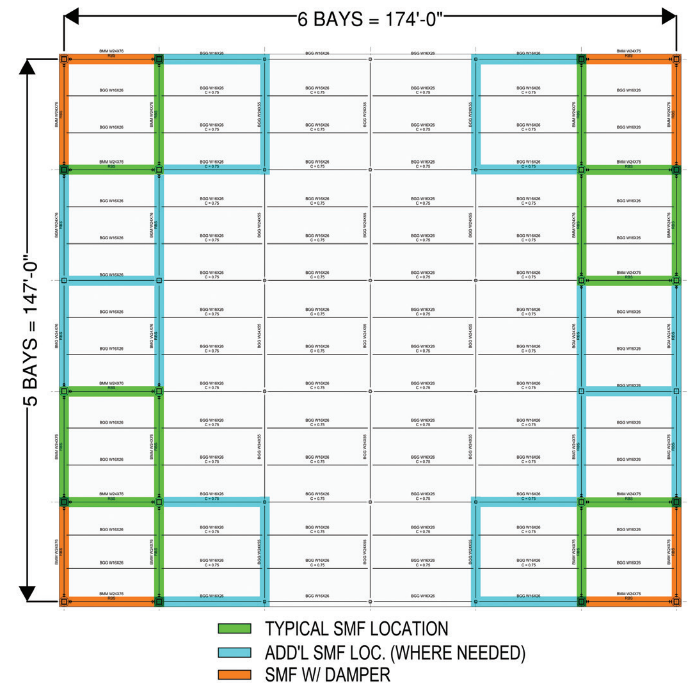

Fig. 2. The archetype 6-story building in the case study has the same rectangular floor plan. Dampers were added to the corners of each floor.

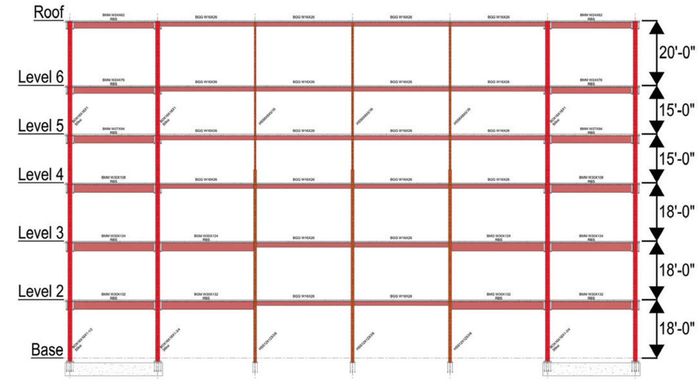

Fig. 3. Shown is the typical frame elevation of the archetype building. The structure is 104 feet tall.

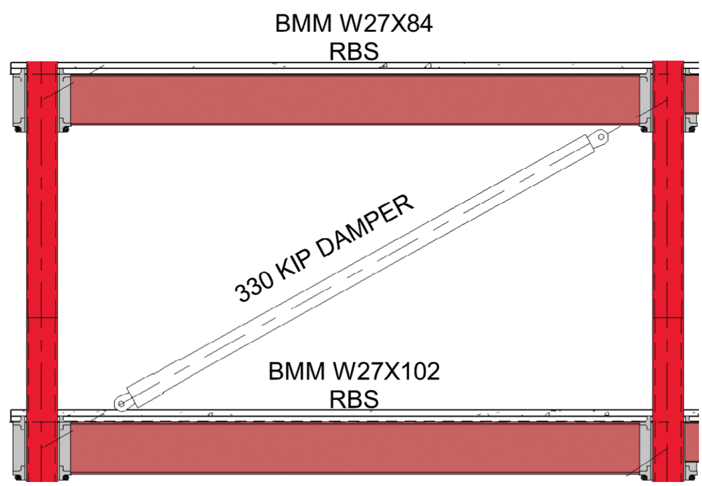

Fig. 4. Dampers were added using a single diagonal configuration.

Case Study: 6-Story Building

The case study analyzes an archetype 6-story building located near Salt Lake City, Utah. All stories have the same rectangular floor plate with a total building height of 104 feet (Figs. 2-3). The building is in Seismic Design Category D with $S_{DS} = 1.062$ and $S_{D1} = 1.042$.

This building was designed in six different ways: RC II, III, and IV, with and without dampers. For the buildings with dampers, dampers were added to the corners on each floor using a single diagonal configuration (Figs. 2 and 4). For the RC III and RC IV designs, additional dampers were added in the lower stories to keep the damper force below a threshold needed for the connection design.

Analysis Procedures

ConXtech analyzed the undamped structures using the MRSA procedure in ASCE 7-16 §12.9.1 and the damped structures using the prescriptive procedure in ICC ESR-4769 with the modified displacement amplification factor ($C_d = 4½$) and reduced base shear scaling. Centerline modeling without rigid end offsets was used to align with ConXtech's prequalification test results. The low aspect ratio of the concrete-filled floors and roof justified rigid modeling for the diaphragms. With $\rho = 1.0$ and no torsional irregularities, story drifts were measured at the diaphragm center of mass per ASCE 7-16 §12.8.6.

Design Process

ETABS software by Computers & Structures, Inc., was used for frame analysis and AISC 360 design checks, including composite column design with axial and bi-directional bending (PMM) interaction. All SMF beams used RBS cuts modeled explicitly to capture their effect on frame stiffness and to check the reduced section for load combination forces. Seismic detailing checks in accordance with AISC 341-16 §E3 and AISC 358-16 Ch. 10 were performed externally.

Initial Frame Design

The moment frames in this case study were designed using the Effective Length Method (AISC 360-16 App. 7.2); all scenarios except RC II Damped had B2 < 1.1, permitting K = 1.0 for frame column design. As a highly distributed space frame, seismic axial loads in biaxial columns were below the 20% threshold of ASCE 7-16 §12.5.4; seismic loads were applied independently in the two orthogonal directions. The design initially ignored damper forces on the frames but later included them during final verification. For the Moment Ratio check in AISC 341-16 §E3.4a, the biaxial SMF columns were designed with sufficient strength to force hinging in all SMF beams in both directions simultaneously. Table 2 summarizes the LFRS designs.

Damper Design

Damper properties were selected based upon a required 25% viscous damping at the DE level. The velocity exponent was 0.4 for all dampers (mandated by the ICC ESR-4769 procedure) and prescriptive equations were used to determine the damping constant, C. Table 3 summarizes the damper properties and forces for the three damped structures. Due to building symmetry, the dampers were the same in both response directions.

Table 2. Frame Design Summary

Story	RC II – Undamped	RC II - Damped	RC III – Undamped	RC III – Damped	RC IV – Undamped	RC IV – Damped
	SMF Beams (Collar Qty.)	SMF Beams (Collar Qty.)	SMF Beams (Collar Qty.)	SMF Beams (Collar Qty.)	SMF Beams (Collar Qty.)	SMF Beams (Collar Qty.)
Roof	W24 (20)	W21 (16)	W24 (24)	W21 (22)	W24 (32)	W21 (32)
Level6	W24 (20)	W24 (16)	W24 (28)	W24 (22)	W24 (36)	W24 (36)
Level5	W27 (20)	W27 (16)	W27 (28)	W27 (24)	W27 (44)	W27 (40)
Level4	W30 (24)	W27 (20)	W30 (32)	W27 (28)	W30 (50)	W30 (40)
Level3	W30 (24)	W30 (20)	W30 (36)	W30 (28)	W30 (54)	W30 (40)
Level2	W30 (24)	W30 (20)	W30 (36)	W30 (28)	W30 (54)	W30 (40)
Total	132	108	184	152	270	228

Table 3. Damper Designs Per TDMF Design Procedure

Story	Risk Category II			Risk Category III			Risk Category IV		
	Total Quantity	C (k-(s/in)$^{0.4}$)	MCE_R Damper Force (kips)	Total Quantity	C (k-(s/in)$^{0.4}$)	MCE_R Damper Force (kips)	Total Quantity	C (k-(s/in)$^{0.4}$)	MCE_R Damper Force (kips)
Roof	8	53	193	8	61	220	8	81	288
Level6	8	81	267	8	107	351	8	141	453
Level5	8	107	352	8	141	456	8	186	592
Level4	8	141	492	8	162	549	12	162	538
Level3	8	141	492	12	123	421	12	186	623
Level2	8	186	608	12	141	450	16	162	508

Damper Forces on Frames

Damper forces were combined with seismic demands per the prescriptive procedure, with 100% of the seismic load and 70% of the damper load (capturing out-of-phase behavior) and vice versa. ConXtech checked the shared DF/SMF beams for P-M interaction on the full beam section. The RBS was checked to ensure sufficient axial capacity to transmit the overstrength damper forces, but as a hinge element it was not deemed necessary to check the RBS for combined seismic and damping forces. For the shared DF/SMF columns, vertical damper forces (modeled as point loads) from each orthogonal frame direction were considered independently for strength checks using load combinations without overstrength on the seismic load effect.

Damper Connections

Double gusset plates connect the dampers to the beam-column joints at each end of the dampers; the gussets connect to the damper clevis with pins. Considering the shallow brace angles in most stories and the desire to keep the gusset plate clear of the collar parts, ConXtech opted to connect the gusset plates only to the beam (Fig. 5).

Special Case 3 of the Uniform Force Method (AISC Design Guide 29 §4.2.4) provided a suitable model for the load path for the damper forces through the gusset plate and the beam. Collar bolts were checked for combined shear and flexure including moments from the gusset-to-beam interface. Complete-joint-penetration welds connect the gusset plates to the SMF beam flange; stiffener plates prevent flange local bending due to the offset between the beam web and the double gusset plates. With a maximum prequalified beam flange width of 10½ inches, the connection detail accommodates a 575-kip damper or smaller.

Moment Ratio Revisited

Adding gusset plates increased the RBS "a" dimension beyond the prequalification limits in AISC 358-16. Provided all other design checks are satisfied, this is acceptable because all the inelastic behavior will occur in the "b" dimension. Checking the projected maximum probable moment against the expected plastic moment of the full beam section limited the length of the gusset-to-beam interface. Reducing the "b" dimension to the minimum value of 0.65d helped alleviate the increase in shear amplification. The reserve capacity of the collar bolts was sufficient to accommodate the additional demand. The Moment Ratios were verified for the increased "a" dimensions and the damper axial forces.

System Resiliency Comparison

The Seismic Performance Prediction Platform (SP3) by Haselton Baker Risk Group LLC was used to explore resiliency metrics for the six archetype structures. SP3 operationalizes the FEMA P-58 and ATC-138 frameworks to determine probabilistic distributions of metrics such as

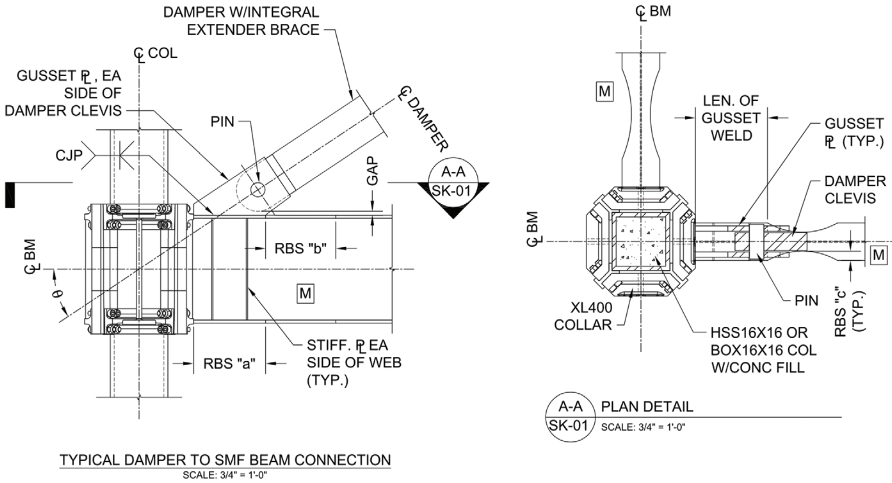

Fig. 5. The gusset plate was connected only to the SMF beam with an RBS cut at the collar.

Table 4. Steel Frame Weight Comparison

Risk Category	Undamped (Tons)	Damped (Tons)	Delta (Tons)	Delta
II	1,036	880	-156	-15%
III	1,311	1,072	-239	-18%
IV	1,920	1,542	-378	-20%

expected loss and downtimes following a seismic event. Building specific structural properties were used along with default content libraries and fragility curves based on RC.

Figure 6 shows the median recovery times for the six archetype structures to achieve Reoccupancy, Functional Recovery, and Full Recovery. Non-zero median recovery times at the DE and MCE_R are shown. Combining dampers with SMFs led to lower recovery times for each archetype and at every hazard level. Functional and full recovery downtimes were attributed mainly to damage to the elevators, facades, and HVAC systems. Residual drift was also a noteworthy contributing factor for the Undamped RC II at the MCE_R hazard. Loss of functionality to elevators and HVAC systems were the largest contributors to extended timeframes for Functional and Full Recovery at the DE and MCE_R hazards. The time required for a contractor to get setup to fix those elements almost uniformly pushed median recovery times to 100 days or more once those elements lost functionality.

Study Results & Conclusions

Table 4 compares steel frame weight for the undamped and damped scenarios. Incorporating dampers reduced total steel weight by 15-20% for all Risk Categories while providing higher resilience vis-à-vis the undamped scenarios. This study found that the cost of the dampers and connections were more than the savings in steel, but foundation savings due to reduced base shear and overturning would help offset this premium.

The following recommendations are given for designers using the XL400 moment frame with the TDMF procedure.

- Use RBS cuts on all shared SMF/DF beams to ensure the plastic hinge forms beyond the gusset plate attachment.
- Limit the damper size to 575 kips to fit the gusset plate attachment in the lengthened "a" dimension; use the minimum "b" dimension to mitigate shear amplification.
- Use single-diagonal damper configurations for shallow brace angles, improving damper efficiency and ensuring the gusset plate attachment to the beam only.
- Perform the Moment Ratio for shared SMF/DF columns as usual; include the lengthened "a" dimension.

This case study demonstrated that combining rapid construction systems with improved prescriptive damper methods can create more resilient structures with a lower carbon footprint. ▪

Full references are included in the online version of the article at **STRUCTUREmag.org**.

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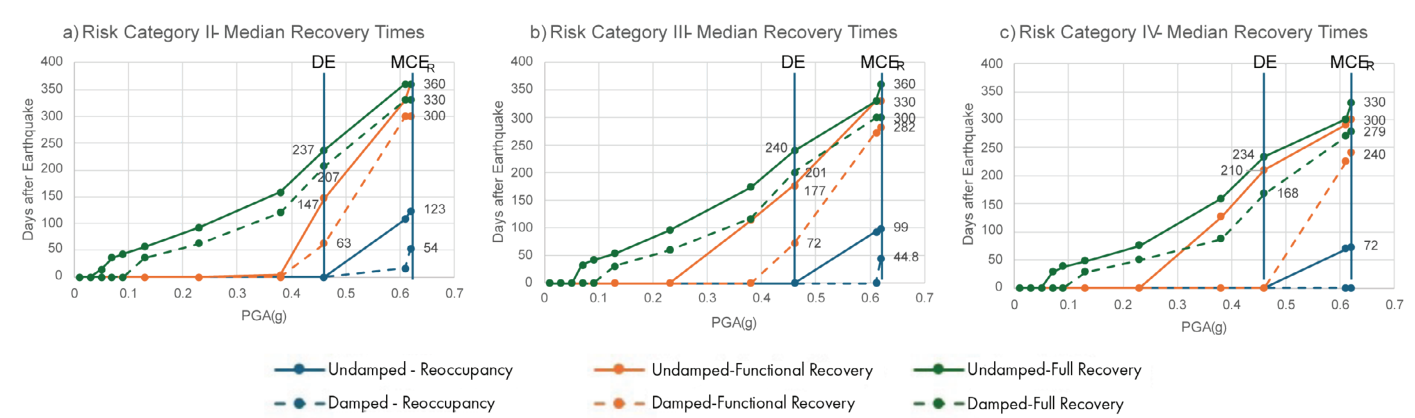

Fig. 6. Median Recovery Times with and without dampers: a) RC II, B) RC III, C) RC IV