Propped Shear Walls

Combining Steel Braces and Concrete Shear Walls for Seismic Strengthening of Existing Buildings

By John Wolfe, S.E., David Mar, S.E., and Steve Tipping, S.E.

The I. Magnin Building, Oakland, CA. Rendering by Thai Nguyen.

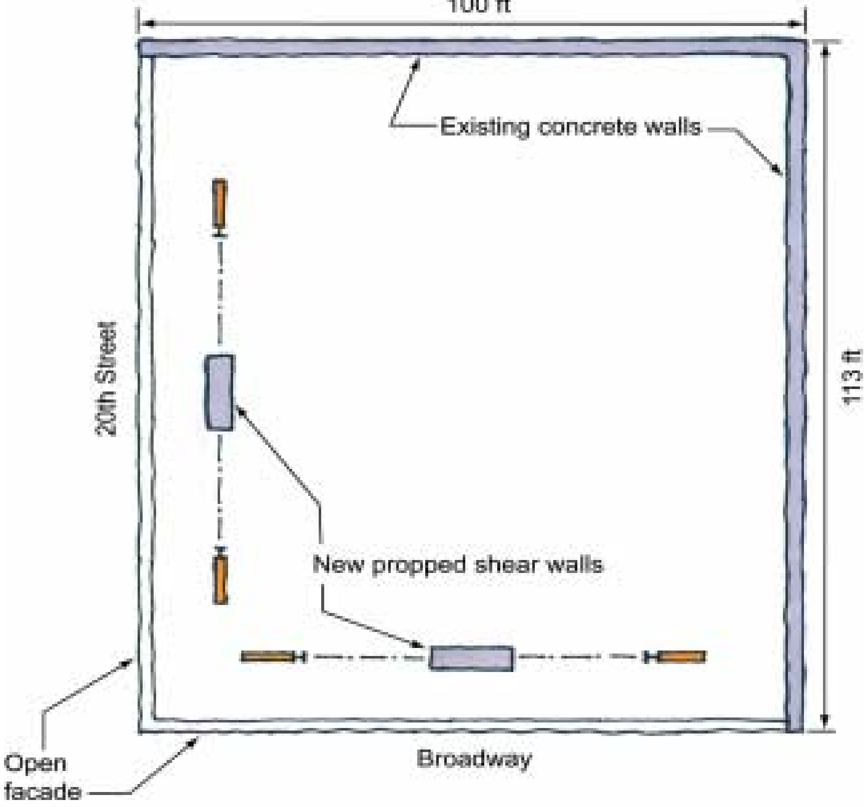
Seismic rehabs are tough. Existing construction, the architect's program and/or the developer's drive to lower costs often restrain engineers. Traditional solutions include concrete shear walls and steel braced frames—systems that work well but can disrupt the architectural program—and moment frames—a system too flexible to protect existing façades. To this end, propped shear walls can often satisfy disparate project demands and budget constraints.

A propped shear wall is a unique steel and concrete bracing system for retrofit seismic strengthening of existing buildings that combine friction damping with the best aspects of steel braces and concrete shear walls. This system creates a high-performance lateral bracing system that is less expensive and less architecturally intrusive than either steel braced frames or concrete shear walls acting alone. The system consists of a tall slender concrete shear wall "propped" near the top with multi-story diagonal steel braces. During large earthquakes, the slotted bolted friction connections of the steel props, along with flexural yielding at the base of the shear wall, provide seismic energy dissipating mechanisms.

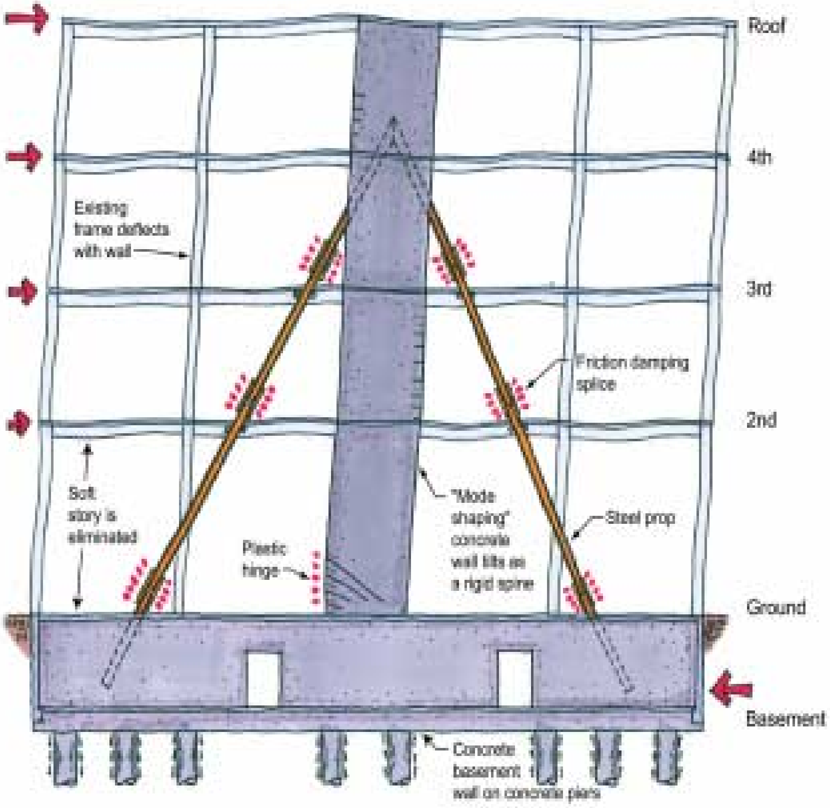
Tipping Mar has used this strategy in the seismic retrofit of twenty structures in the earthquake-prone San Francisco, CA, bay area. In this article, the most recent propped shear wall projects will demonstrate how this lateral strengthening system works.

The I. Magnin Building, Oakland, CA

The most recent building retrofitted with propped shear walls is the I. Magnin building at 2001 Broadway, Oakland, CA. Constructed in 1930, the building is a well-known landmark in downtown Oakland, sporting a green terra cotta and serpentine stone façade. The structure, a flexible and tough four-story riveted steel frame measuring approximately 100′ by 113′ in plan, contains a basement and large penthouse. Existing floors are reinforced concrete slabs spanning between steel beams, and existing steel beams and columns are encased in concrete fireproofing. The steel columns are founded on concrete piles.



Schematic plan. The two heavily fenestrated façades cause a significant plan torsional irregularity.



Deformed shape of propped shear wall.

Plan Torsion, Soft Story and Soft Soil Challenges

The building's geometry and site geology pose special seismic risks. Due to its corner location, the building has open fenestration along the street sides and solid concrete infill walls between the steel frames on the back two property lines. As demonstrated in the aftermath of many earthquakes around the world, such corner buildings can be very susceptible to plan torsion damage. Under this twisting or rotation, the front street façades, and especially the outermost street-side corner, can sustain extensive damage and potentially even partial collapse.

Compounding the torsion problem, the building also has a tall "soft" first story, 24′ tall in contrast to the 16′-6″ tall typical stories above. Deformations and damage will concentrate in this soft story rather than being distributed more evenly over the height of the building.

Finally, the site has special geological liabilities: the upper soil layers are relatively soft clays that lengthen the soil period under ground shaking, and the building is located only three miles from the Hayward fault.

The Retrofit Criteria

Under Oakland's building code, this was considered a voluntary seismic retrofit, and the owner had some latitude in selecting the retrofit design criteria. Like many retrofits of existing buildings in the San Francisco bay area, lateral design forces for this project were set at 75% of the 1994 UBC lateral force levels. This reduction in design force level increases the chance of exceedance from 10% in fifty years for modern code to 20% in fifty years for this retrofit (see FEMA 273 for more information).

Slotted bolted prop connection.

The new and the old: props appear alongside a 1930s vintage riveted steel transfer girder.

The Propped Shear Wall Solution

The developer, SRM Associates, decided to seismically strengthen the building as part of the renovations for the new tenant, DoubleTwist. Propped shear walls provided the least architecturally intrusive solution, allowing an open office environment at the upper floors and open retail spaces, required by the city of Oakland, on the first floor. The exposed W14x211 props provide reassuring muscular bracing and an interesting architectural feature to the office and retail spaces.

To fight both the plan torsion and soft story problems, the propped shear walls are located 12′ away from the windows on both the street sides of the building. Each vertical concrete shear wall, three feet wide and 12′ long, extends the full height of the building. The steel props intersect the walls at the top floor. Each wall and pair of props are anchored in a common basement shear wall. This basement wall stands on a series of three-foot diameter by 50′ deep drilled piers.

Seismic forces are gathered from the floor slabs and transmitted to the shear wall via heavy steel angle collectors fastened to the underside of the concrete slabs with epoxy-grouted bolts. The angles are spliced by extending $2^1/_2$”-diameter A36 rods through holes cored through the webs of the existing beams.

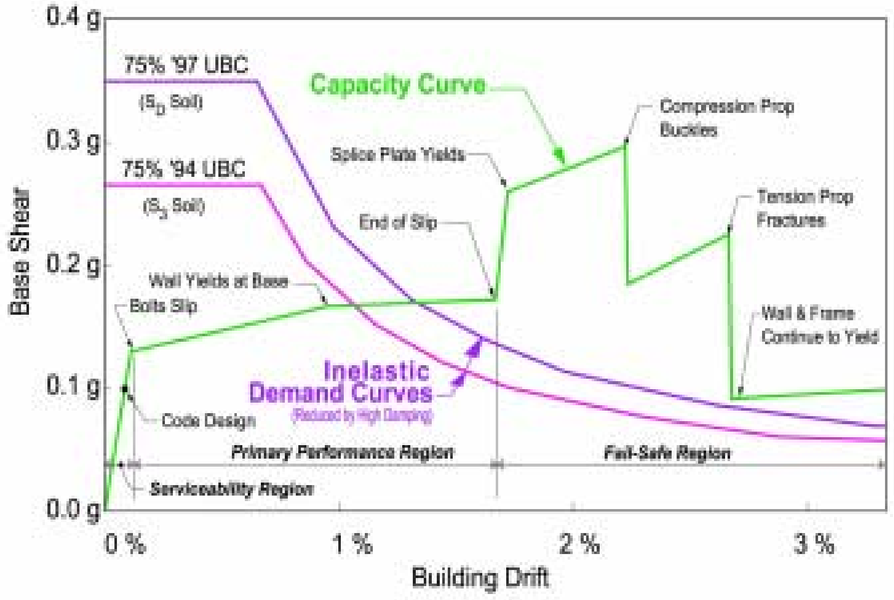
Slotted Bolted Energy Dissipating Connection

The prop's connections act as energy-absorbing dampers under large earthquakes. The friction connection is made up of bolted splice plates that clamp onto the prop. The prop has long slotted holes and brass shims that are inserted between the prop and splice plates. The brass shims, with their predictable friction coefficient, along with a preset bolt clamping force, give the damper slip force. The design of the prop connections are based on experimental research by Popov, Grigorian and Yang of the University of CA at Berkeley (UCB/EERC Reports 92/10, 94/02 and 95/13). The connection splice plates are $^5/_8$” thick Bethlehem Steel V-Star plates with a Charpy V-Notch toughness of 150 ft.-lb at 0 °F. The bolts are pre-tensioned to 66 kips, based on a coefficient of friction of 0.30, to slip at slightly above code design force levels. The connection is designed so that bolt slip and ductile plate yielding occur well before non-ductile bolt shear or W14 fracture. The tough plate material ensures that the splice plates will yield in tension rather than fracturing.

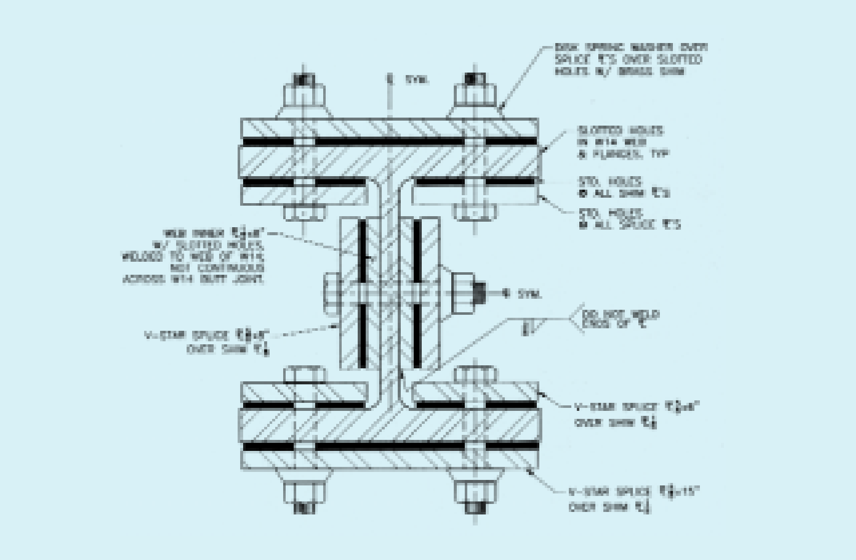
Inelastic Response During “the Big One”

The effectiveness of the friction-damped propped shear wall solution is best understood in light of the existing structure's characteristics and vulnerabilities. Tipping Mar's strategy implements a system that works with the existing structure to simultaneously correct its weaknesses, activate its strengths and protect the architectural finishes for medium levels of ground shaking.

The propped walls are initially rigid up to moderate levels of shaking, because the friction splices hold without slipping and protect the brittle façade. For rare and intense ground shaking, the friction dampers slip and the shear wall hinges at its base and rocks as a rigid element. This adds strength, stiffness and damping while resisting the dominant torsion mode and eliminating the soft story. The plastic hinge above the foundation forces a tilting mode, since the wall acts as a tall rigid spine. This “mode shaping” creates a uniform distribution of drift over the height of the building, preventing soft story and higher mode effects that can cause destructive concentrations of drift and damage. This works well with the existing flexible steel frame, uniformly distributing rotation demands over all the beam-column joints in the building.



Inelastic demand and pushover curves for the 2001 Broadway retrofit.



Section at prop splice.

The inelastic characteristics of the propped shear wall system can be illustrated by a static nonlinear "pushover analysis". Earthquake demand and building capacity are plotted as two separate curves on a graph of force versus displacement. A descending curve represents the earthquake inelastic demand, with demand forces generally decreasing with increasing deformations. Hysteretic damping by the prop friction connections greatly reduces the inelastic demand curve. The retrofitted building's capacity ("pushover") curve rises steeply in the "serviceability region," flattens out over the "primary performance region" and maintains lateral resistance over the large-deformation "fail-safe" region. The pushover curve of a successful seismic design crosses over the earthquake demand curve, indicating that the structure still has some reserve strength and ductility and will not collapse.

The inelastic demand and pushover curves for the 2001 Broadway retrofit are shown at left. In small earthquakes and low seismic forces, the prop connections do not slip, the system is very stiff and rigid and the pushover curve rises steeply. This provides good serviceability, protecting non-structural elements such as partitions, windows and façades from damage. Under large earthquakes, seismic forces will exceed the code elastic design forces, and the slotted bolted connections will slip. As the connections slide back and forth over the internal brass shims, tremendous amounts of seismic energy dissipates in nearly rectangular hysteresis loops. When the prop connections slip about an inch, the concrete shear wall will begin to yield at its base. This will also dissipate large amounts of seismic energy. The pushover curve flattens out at bolt slip and wall yielding and extends far enough to cross the earthquake demand curve, indicating a successful design.

Under "the big one," the milled ends of the props may butt together and the bolts may slip to the end of their travel. Forces on the connections will rise rapidly until the notch-tough V-Star splice plates begin to yield and stretch plastically. Under this stretching, the splice plates will strain harden, and forces will increase until eventually the compression prop buckles. Even after the compression prop buckles, the splice plates in the tension prop will continue to stretch. The pushover curve rises, descends steeply at the point of buckling and then flattens again. Even in the unlikely event that under enormous deformations the splice plate or W14 eventually fractures, the no-longer-propped cantilevered shear wall has more than sufficient base moment capacity and ductility to resist P-delta effects under large seismic drifts, and thereby prevent collapse.

Propped Shear Walls as Architectural Features

The propped shear walls provide distinct architectural advantages. Kevin Ames, project manager for the developer, SRM Associates, notes: "In our renovation work, we make every effort to not only create the most viable space for the building users but also preserve as much of the existing historic fabric as possible. The propped shear wall solution seemed to make sense for the I. Magnin Building in terms of visually preserving its classic art deco façade, while retaining the maximum level of 'openness' for the interior plan layout."

Because the diagonal steel props resist forces only during earthquakes, they do not need to be fireproofed and can be concealed in partition walls or left exposed. The project architect, Eric Ibsen of Ibsen-Senty Architecture, took full advantage of the propped shear walls: "We recognized the propped walls as distinctive steel and concrete elements in what is principally an open office space. By using them as an architectural feature, they became a catalyst around which we designed the feature conference rooms at each floor."

Fabrication, Erection, Budget and Schedule

Steel erection was straightforward and proceeded on schedule. Project manager Bruce Cox notes: "The erection went smoothly under a very aggressive schedule. While the prop-wall work point had a construction tolerance of plus/minus $^3/_4$", we hit the mark within $^1/_8$" on both walls. This was also an interesting project for us, since brass shims, Belleville washers and V-Star plate are new ingredients for us."

Total structural cost of this retrofit in the San Francisco bay area's overheated construction market was about $1,735,000, or roughly $27.50 per sq. ft. The structural steel portion of this budget was about $664,000. Ed Todd, vice president of Westfour Corporation (the general contractor), notes that the two main challenges for this project were "the constant fight for manpower in this tight labor market and the logistics of getting materials and tradespeople in and out of this tight site."

Propped shear walls provide an attractive, effective seismic retrofit strategy for mid-rise buildings. Structurally, the system provides good initial lateral stiffness, excellent ductility and high damping. Architecturally, the props and walls accommodate varied space plans and visually complement the original construction of renovated buildings.

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