New Strategies in Seismic Design for Timber Frame Structures

STEPHEN DUFF
University of Oregon

INTRODUCTION

Assessment of damage in recent severe earthquakes has demonstrated the need for the development of reliable and economical technologies for improving the seismic performance of woodframe buildings. Over half of the $40 billion property loss sustained in the 1994 Northridge Earthquake occurred in wood structures[1]. Of the 25 fatalities caused by building damage, all but one occurred in woodframe construction[2].

The seismic response of timber structures is predominately controlled by their connections, and when they are loaded to failure, damage is concentrated at the joints. Moreover, notable stiffness and strength degradation and hysteresis pinching is observed in typical timber connections when they are subjected to strong cyclic loads (Fig. 1). As steel components yield, non-reversible crushing of wood fibers occurs and slackness in the connection develops incrementally. This local phenomenon is very detrimental to overall building performance. It is appropriate, therefore, to consider alternate connector strategies to mitigate these shortcomings.

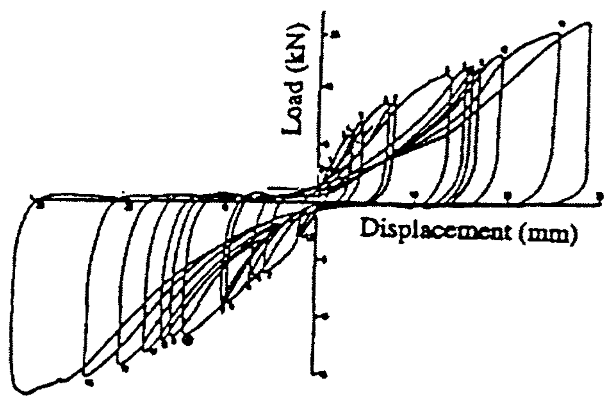


Fig. 1. Typical hysteresis shape for wood joint with a yielding bolt (Dowrick 1986).

Slotted Bolted Connections (SBCs) are simple friction dampers which provide an effective means for controlled, non-destructive hysteretic energy dissipation in structures subjected to severe seismic loading. SBCs have notable economic and practical advantages: simplicity of design, the use of off-the-shelf hardware and standard fabrication techniques, the absence of exotic materials and precision manufacturing, and the fact that SBCs exist in the public domain.

Previous research conducted by the author suggests that SBCs are a viable strategy for use in engineered timber structures. Results from proof-of-concept experiments evince that the potential performance of SBCs in timber joints is admirable: only slightly pinched, near rectangular hysteresis loops are produced with negligible strength and stiffness degradation.

This paper presents basic concepts and design features of SBC connections, describes their observed behavior, and introduces new design strategies for seismic design of timber frame buildings.

SLOTTED BOLT CONNECTIONS

SBCs are modified bolted shear-splice connections (Fig. 2). A typical SBC consists of two outer plates "sandwiching" a third inner plate, with normal force provided by high strength pre-tensioned through-bolts and special steel washers. The bolts pass through standard holes in the outer plates and through slotted holes in the inner plate, allowing the inner plate freedom to slide relative to the outer plates and bolts. Brass or bronze shims are used to improve wear and friction behavior.

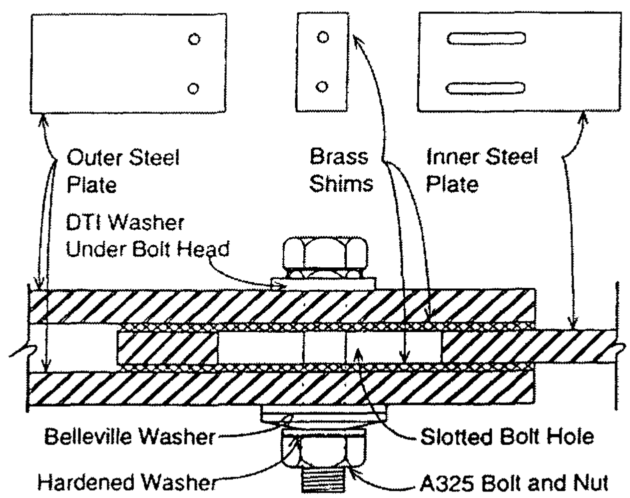


Fig. 2. SBC schematic drawing.

A typical bolt assembly consists of a structural steel bolt, a hardened flat washer, a Belleville conical compression washer under the nut, and a Direct Tension Indicator (DTI) washer under the bolt head. Belleville spring washers have been shown to mitigate observed reductions in normal force due to bolt loosening caused by creep and wear processes. DTIs are used to determine bolt preload (a measurable gap between the bolt head and washer face closes when small projections on the washers deform as the bolt is tightened) .

Under rectilinear tension and compression cycles, the inner plate slides back and forth between the outer plates with a relatively constant and predictable slip force.

FRICTION AND WEAR MECHANISMS

Tribology is the interdisciplinary field of science dealing with friction, wear, and lubrication. Of immediate concern to the reader is a preliminary understanding of the law of Coulomb friction and of wear mechanisms in a given tribosystem.

The kinetic slip force of a steady-state system is defined here as the instantaneous tangential force required to keep a friction system moving. This slip force is a function of the normal force applied to the friction surfaces and the friction coefficient for the materials in contact. For most systems slip force is independent of the apparent area of contact. Kinetic slip force is affected by slip velocity, but for practical purposes, kinetic friction coefficients may be taken as constant within limited velocity ranges[3]. In an SBC the kinetic slip force is calculated as the product of the normal force per bolt (N), the number of bolts (n_b), the number of surfaces in friction (n_s), and the appropriate kinetic friction coefficient (μ)[4].

$$F_{slip} = N\, n_b\, n_s\, \mu$$

Friction systems experience complex transition processes and wear phenomena[3,5]. Under steady-state conditions, the faying surfaces in a metal-on-metal friction damper exhibit both adhesive and abrasive wear, which give rise to surface changes and debris shedding, and a subsequent reduction of bolt normal force and slip force. Estimation of wear volume in a friction system is given by the Holm equation[3], in which it is seen that wear volume is proportional to the normal force, the cumulative distance of travel, and the wear coefficient; and is inversely proportional to the penetration hardness of the softer material. Qualitative estimation of the wear coefficient suggests that predicted wear volume in a brass-on-steel system is less than in an equivalent steel-on-steel system by a factor of 25[4].

In steel-on-steel SBCs, wear, bolt loosening, and slip force reduction is severe, while in steel-on-brass SBCs, wear is much reduced and slip forces are relatively constant[4]. It is for this reason that brass shims are used in the assembly.

HYSTERETIC BEHAVIOR

The hysteretic behavior exhibited by an SBC can be idealized as elastic-perfectly-plastic, and is characterized by a break-in phase prior to the onset of steady state behavior (Fig. 3)[5]. Following initial elastic deformation (a), the static slip force is exceeded and a small sudden drop in slip force is seen at the onset of sliding (b). The subsequent break-in phase is characterized by a break-in curve with a shallow positive slope over a cumulative travel distance between 0 and about 25 cm. (c)[4]. Monotonic increase in slip force during break-in is common in friction systems and is denoted as "type-a" behavior[5]. Steady state conditions are said to exist when the mean kinetic friction coefficient, wear rate, and other parameters (and thus the mean kinetic slip force) have reached and maintain a relatively constant level (d)[5].

PROPOSED SBC TIMBER CONNECTIONS

Several strategies for using SBC dampers in timber buildings are being developed by the author at the Design Build Research Laboratory at the University of Oregon[6]. Three of these are briefly presented here.

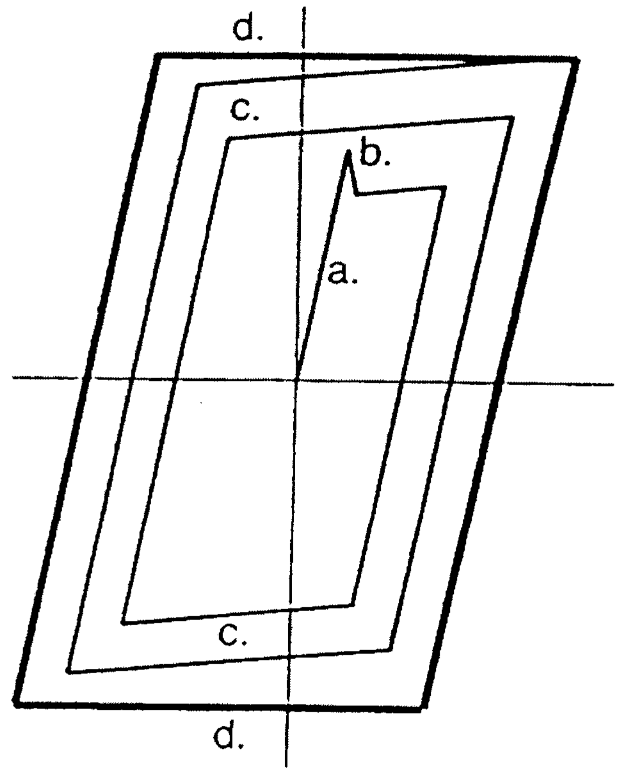


Fig. 3. Idealized SBC behavior.

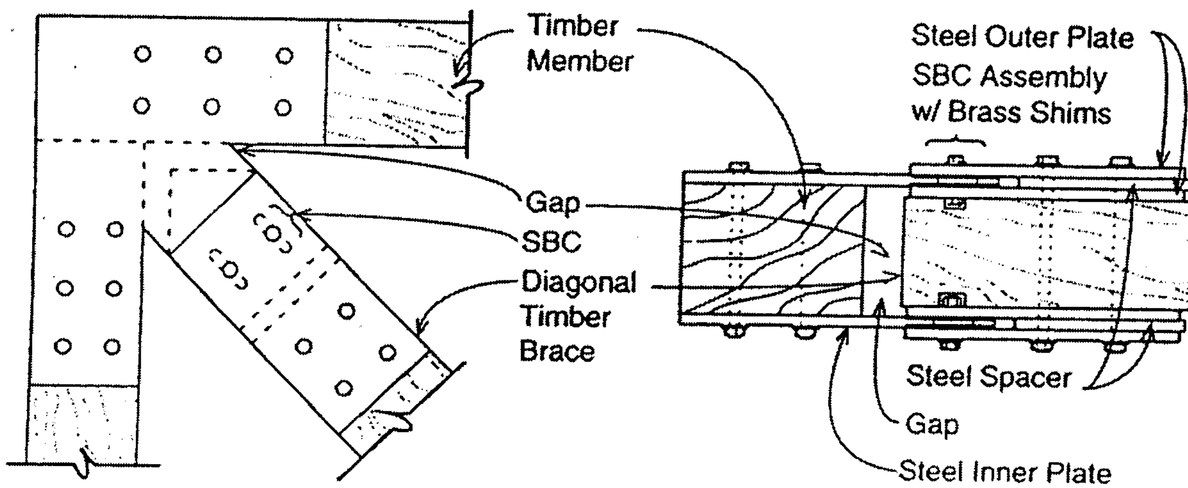
For typical diagonally braced wood structures with bolted connections and exposed steel side plates, a cost effective damper can be built by modifying the steel side plates and adding a spacer. In Figure 4, two modified SBC assemblies are shown bolted on opposite sides of timber members at a concentric joint between a diagonal strut and a beam-column. A gap is left between the end of the brace and the beam-column intersection to allow for both positive and negative displacements of the damper.

Two strategies for slotted bolt moment connections for use in portal frames are more tentatively introduced. In the first schematic design (Fig. 5), a curved slot is machined in the inner plate, and a large diameter pivot pin connects the outer and inner plates. If rotational displacements were imposed on the beam, it would rotate about the pin relative to the column, with damping provided by the SBC assembly in the curved slot. In this figure, the method of fixing the plates to the timber members with bolts is schematic only; alternate methods might prove more satisfactory. Buckling of the side plates is a also a concern and requires study.

In the second schematic design of a SBC moment connection (Fig. 6), SBC assemblies are bolted to the top and bottom faces of the beam, and flat plates with a pivot pin are fixed to the side faces. This configuration has been tested on a large steel beam-column connection with excellent results[7].

HYSTERETIC BEHAVIOR OF SBC TIMBER CONNECTIONS

Proof-of-concept experiments conducted by the author and published elsewhere[8,9] have yielded promising results. For an alternate specimen configuration (not shown here) with a gap between the an axially loaded longitudinal member and a transverse beam, the hysteretic behavior was excellent (Fig. 7). At the onset of loading, a small gap between the damper and the mortise closes and the system deforms elastically. As the damper begins to slip, an



ig. 4. Schematic design of external bolted plate damper for concentric bracing.

expected sudden drop in slip force is observed, followed by a break-in period during the first four and a half cycles (a cumulative travel distance of about 17 cm). During the final four cycles, steady state behavior is observed, with near constant slip force.

It will be noted that the loops are slightly pinched due to a plateau of zero stiffness at the point of load reversal. A small plateau is observed during the initial elastic cycles (due to the gap between the damper and the mortise), and as the wood crushes under the end bearing plates with increasing load, this gap increases in size, and the plateau lengthens.

The behavior of a specimen without a gap is worth noting. During the tension phase of the load cycles, the observed behavior follows the same pattern as that shown in Figure 7. During the compression phase, however, as the longitudinal member bears up against the transverse member, the damper cannot slide and a sharp downwards spike is produced as the load increases. This spike would continue to develop until the transverse member failed in bending or shear. The damping characteristics of a connection without a gap between members is consequently inferior.

DAMPING POTENTIAL

Although the results presented above are from experiments conducted under pseudo-static cyclic loads with no inertial or other time-dependent effects influencing the response, they give a reasonable picture of the behavior of a slotted bolted timber connection. Under dynamic loads, it is possible that the break-in and steady state curves would change slightly[4]. The plateau at load reversal might differ slightly due to the effects of load duration and repetitive load cycling .

For a steady state cycle in the response shown in Figure 7, preliminary calculations give an equivalent viscous damping of about 57 percent (= 63.7 percent for rigid-perfectly-plastic behavior). If imposed displacements do not exceed the stroke of the SBC, previous research has shown that the dampers can experience multiple load cycles without an appreciable drop in slip force (tests have been conducted with cumulative travel distances reaching nearly 10 times the cumulative brace travel expected in frames subjected to severe earthquake loading[4]).

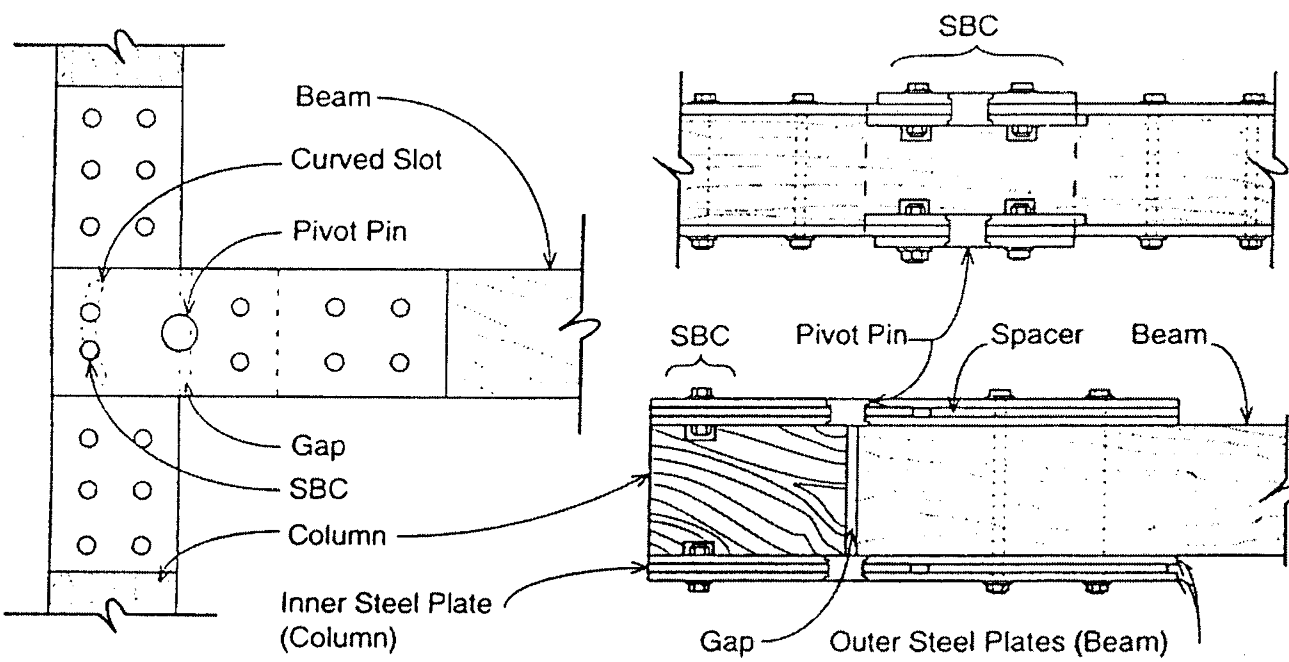
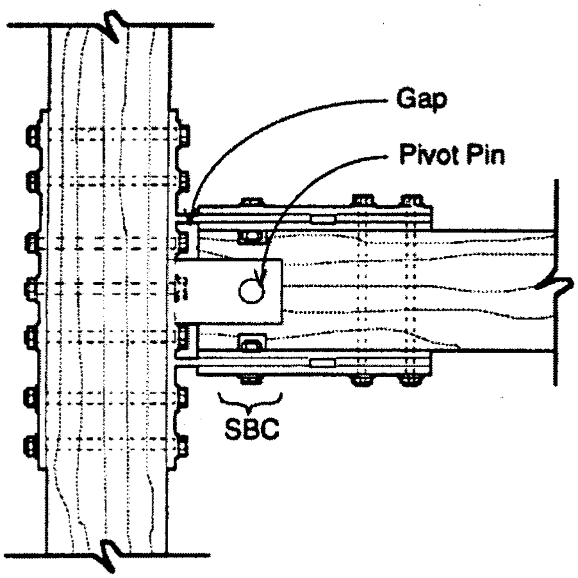


Fig. 5. Schematic design of friction-damped moment connection (1).



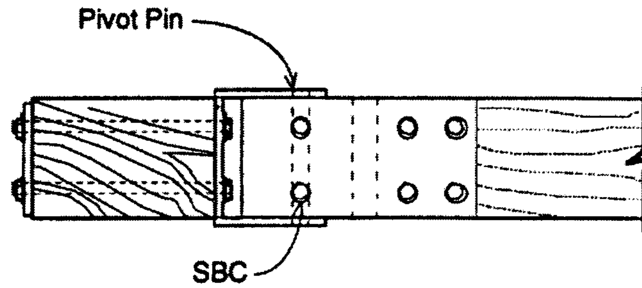


Fig. 6. Schematic design of friction-damped moment connection (2).

It is expected that the effect of SBC connectors on the response of timber frames would be significant. Previous research[10] has shown that on average 85% of total simulated seismic input energy is dissipated by a SBC damper in a simple braced steel frame (Fig. 8), with the SBC preventing buckling and yielding of the diagonal brace. Similar results are expected in braced timber frames.

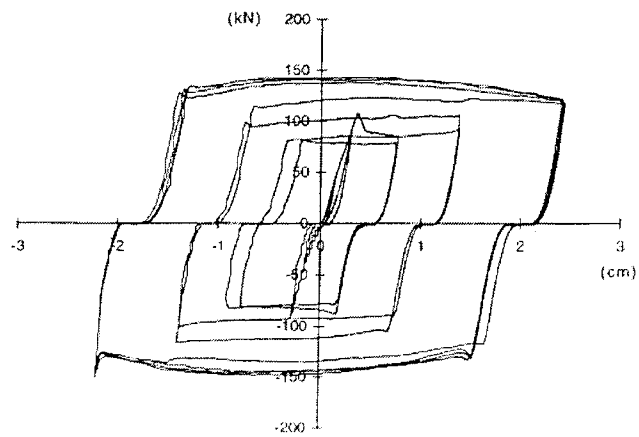


Fig. 7. Hysteretic behavior of a SBC friction damper with a gap between timber members.

In correctly designed structures, judicious use of SBCs may result in damage being localized to the SBC. If so, damage would then be reversible: after slipping, SBCs can be re-centered by jacking the plates back to their initial positions. Additionally, given that slip force in SBCs is predictable, it may be possible to "tune" engineered timber structures for desired behavior by tightening SBC bolt preload to desired settings.

FUTURE RESEARCH

Further experimental research is required to test the behavior of SBCs in timber connections, especially under truly dynamic conditions. Experimental study of alternate connection designs and strategies would be useful, as would full scale testing of SBC-damped timber frames. Previous research[4,11,12] suggests that realistic analytical models of SBC-damped timber frames can be developed. Finally, use of SBCs in real timber structures would be informative.

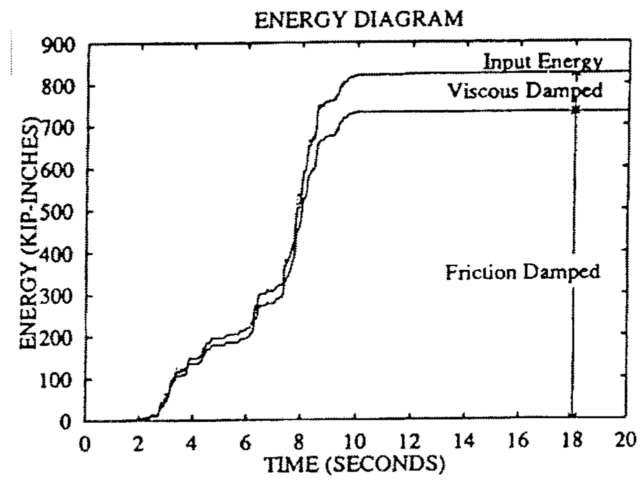


Fig. 8. Energy diagram of response for a simple steel braced frame (Gregorian, n.d.)

CONCLUSION

The damage sustained by wood buildings in recent severe earthquakes has demonstrated the need to develop new technologies for seismic design of timber buildings. Slotted bolt connectors have been shown to exhibit excellent energy dissipating characteristics, and their application in timber structures appears to be very promising. The simplicity, practical advantages, low cost, and excellent behavior make SBCs an attractive means to dissipate the earthquake input energy in timber structures likely to experience severe seismic loading.

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