Supplemental Damping in Woodframe Structures

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Abstract

This paper reviews the state of the art in supplemental damping of woodframe structures and provides suggestions for future research. Work in this area needs to focus on practical and cost-effective methods utilizing innovative supplemental damping systems in panelized construction and retrofit applications. Ideally these systems would be incorporated into the structure such that the finished dimensions are unchanged, and would serve to minimize or possibly eliminate, the need for traditional fasteners for the sheathing and gypsum drywall. Additionally, resources should support investigating systems that provide the flexibility to be used in on-site applications by low skill labor for remediation of existing structures. Woodframe structures continue to experience significant structural and non-structural damage during moderate to large earthquakes. In many cases the structure may remain standing after the disaster, only for there to be serious structural and non-structural damage that renders the residence uninhabitable. Having just high ductility is no longer satisfactory; today's structures must be engineered and designed to perform better and to insure more than just life safety. Increasing the energy dissipation capacity of the primary lateral load resisting system of the structure would significantly reduce the risk to loss of life, injury and non-structural damage during seismic events. Materials and systems proven successful in steel and concrete structures exist and can add significant supplemental damping to woodframe structures. Such systems could radically improve the cyclic performance wood structures, but must not alter the dimensions of the woodframe shear walls or the structure itself. Some of these systems can be placed between the sheathing and frame and between the finish material and frame. The proposed advanced panel systems could drastically reduce labor time and skill requirements by reducing or eliminating the use of conventional fasteners, incorporating finished materials into the panel, and significantly increasing durability, thereby reducing structural and non-structural damage due to natural hazards.

Keywords: shearwall, passive damping, viscoelastic polymer, energy dissipation, seismic protection

Introduction

Low-rise woodframe structures continue to experience structural and non-structural damage during earthquakes. The damage due to earthquakes can be widespread and catastrophic. In Los Angeles County, roughly 60,000 residential woodframe units were significantly damaged and later deemed uninhabitable by the 1994 Northridge earthquake (Holmes and Somers, 1995). The cost of the damage to woodframe structures was estimated at over 20 billion dollars, at least half of the total estimated loss from the earthquake (CUREE, 1999). While life safety and risk of

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injury are important issues with low-rise construction, clearly, structural damage, which is prevalent and has significant costs associated with it, is a problem that must be addressed.

The seismic response of shear walls is governed by their ability to resist cyclic or repeated lateral load. Today, the lateral load resisting systems in woodframe structures are almost entirely comprised of shear walls. In areas of high seismicity, woodframe structures consist of shear walls sheathed with plywood or OSB around the perimeter of the building. The wall resists the lateral load by racking, that is, the stud frame shears while the sheathing rotates. The fasteners attaching the frame and the sheathing bend and elongate. The lateral load capacity of the wall is governed by the load-displacement behavior of the fasteners. Under cyclic loads, the fasteners are repeatedly deformed in opposite directions thereby enlarging the fastener hole in the wood. These enlarged holes leave the wall in a more compliant state for the next deformation. Experimental data from cyclic tests of wood connections and woodframe shear walls show that the wall stiffness decreases with increasing displacement. Furthermore, the stiffness and energy dissipation capacity decrease during constant amplitude cycling (Shenton et. al., 1998), which is representative of seismic loads. Consequently, the strength and the ability to dissipate energy of a woodframe structure subjected to repeated dynamic events degrade dramatically over time.

The past twenty years has seen an explosion in the use and application of innovative systems and materials for seismic hazard mitigation of the built environment. Seismic isolation, passive and active control, and seismic rehabilitation using advanced polymer composite materials are perhaps the best known recent innovations that have had an impact in the design of new structures and the rehabilitation of older, seismically deficient structures. The research into these technologies has concentrated almost exclusively on their use in steel, concrete and masonry structures. With the exception of a few cases that will be mentioned shortly, these advanced systems have yet to be exploited in woodframe construction. These and other innovative, but yet to be discovered, systems and materials have the potential to have a profound impact on the design, construction and rehabilitation of wood structures. Research in this area must focus on how, and to what extent, innovative supplemental damping systems and materials can be brought to woodframe construction to help reduce seismic damage and the economic losses associated with the damage.

Current State of the Art

There has been significant work in the area of cyclic/dynamic testing of woodframe structures; a thorough review of this work can be found in NIST, 1998, CUREE, 1999, and CUREE, 2001. Investigation of cyclic tests have revealed some significant relationships between wall stiffness and energy dissipation capacity and continued cycling (Shenton et. al., 1998). It was found that the stiffness of the wall decreases linearly with continued cycling at the same amplitude and does not stabilize completely after four cycles at the same amplitude, implying that the durability of the wall continues to decrease. The most significant finding was that the energy dissipation capacity of the shear wall decreases by 20% between the first and second cycle of constant amplitude loading.

This State of the Art review focuses on innovative applications of supplemental damping for improving the response of wood structures subjected to cyclic loading. These systems will provide a constant source of energy dissipation that will not degrade during cyclic loadings. While the application of innovative systems and materials in wood structures is not widespread, there has been a marked increase in research in this area in the last five years. This review focuses on recent work, and is divided into four sections; the first three are: 1. Base Isolation, 2. Analytical Investigations (no experimental work), and 3. Experimental Testing (all studies include an analytical component). The fourth section reviews and highlights the experimental and analytical work with viscoelastic polymers that is currently funded by the NSF-PATH program.

Base Isolation

There have been five studies investigating the use of base isolation systems for light-framed wood structures, two of which were purely analytical studies, while three included implementation of different types of devices (Delfose, 1982, Reed and Kircher, 1986, Sakamoto et. al, 1990, Pall and Pall, 1991, and Zayas and Low, 1997). CUREE (2002) provides a detailed summary of these projects.

Analytical Investigations

Filiatrault (1990) analytically investigated the application of passive energy dissipation devices in woodframe walls. He proposed slotted friction devices be used in the corners of panels. Theoretically, as the frame racked back and forth, the slipping of the friction devices would dissipate the energy associated with an earthquake. A single degree-of-freedom model of the wall was developed in which the primary unknown was the lateral displacement of the frame. The response of the wall with and without the friction dampers was computed for three different earthquakes. Results illustrated the clear benefit of the passive energy dissipation devices: larger hysteresis loops, indicating a greater amount of energy dissipation; smaller displacements, and maximum forces less than or equal to those present in the wall without devices. Work was restricted to numerical studies; no experimental tests were conducted to verify the performance or feasibility of the proposed system.

Symans et. al. (2001) numerically evaluated the seismic response of a woodframe shear wall with and without a fluid damper. The damper was introduced via one diagonal brace running through the confines of the wall. Nonlinear finite element analyses showed that dampers could be effective in dissipating a large portion of the seismic input energy. No experimental testing was conducted to validate the numerical findings. This work was conducted as part of the initial phase of CUREE Task 1.4.7, Innovative Systems

Curee (2002a) provides the final work of Task 1.4.7, and includes a detailed analytical study of the effect of fluid dampers on the seismic behavior of a wood shearwall and a three dimensional, two story structure. Again, the nonlinear finite element analyses showed that dampers could be extremely effective in dissipating a large portion of the seismic input energy for the structure. No experimental testing was conducted to validate these promising numerical findings.

Experimental Investigations

Higgins (2001) conducted a wall test with a hysteretic damper. The supplemental damping system was comprised of a diagonal brace with a sliding anchorage at the base corners of the wall and fixed anchors at the top corners. The results of the cyclic testing of one woodframe shearwall with a kinematically expanding damper inserted in each of the diagonal elements within the wall were reported. The damped wall exhibited significantly higher stiffness and energy dissipation capacity than a conventional wall. An accompanying numerical study of a simple structure demonstrated that the proposed supplemental damping system was effective in reducing the peak displacements of the structure subjected to an earthquake.

Dinehart and Shenton (1998) conducted wall tests on a set of four shearwalls with a viscoelastic (VE) damper installed via a diagonal brace. Comparison to conventional wall tests showed that significant increases in energy dissipation could be achieved for all levels of wall displacement. Since this study more than thirty cyclic tests have been conducted on walls that incorporate some form of supplemental damping utilizing VE dampers. Dinehart, et. al., (1999) presented configurations that included corner dampers, sheathing-to-stud dampers, tendon dampers, and a diagonal brace.

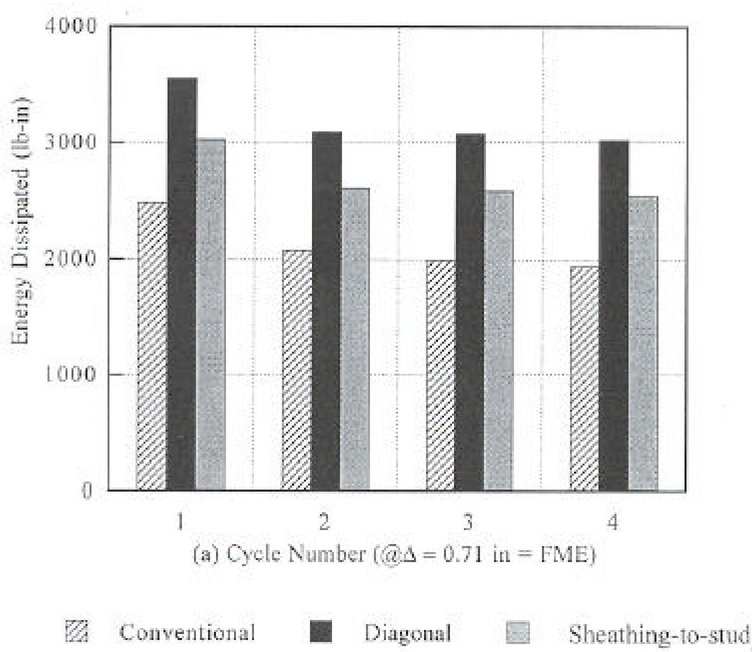

Figure 1: Energy dissipation at constant amplitude cycling amplitude.

Figure 1 shows a comparison of the energy dissipation of a conventional wall with two configurations of damped walls at a wall displacement of 0.71 in. These tests have demonstrated that VE dampers can significantly increase the energy dissipation capacity of the walls. It is clear that the energy dissipation of conventional wall degrades at constant amplitude cycling beyond cycle number 2, but the VE material provides a constant source of energy dissipation. It was also shown that the wall performance could be enhanced without impacting the design, construction, dimensions, or finishing of a conventional wall.

In addition to this work, a numerical study was conducted that resulted in the development of a discrete three degree-of-freedom model of a woodframe shear wall that is capable of capturing the salient features of the wall response. The model is amenable to exact closed-form solution for various excitations, or for conducting time history or response spectrum analyses (Dinehart and Shenton, 2000). The model also has the capability of accounting for the inclusion of VE dampers, as demonstrated by Dinehart (1998).

Alternative Applications of Viscoelastic Material

Dinehart and Lewicki (2001) demonstrated that it is feasible to apply VE polymers directly to wood. They compared the static and cyclic performance of VE dampers constructed from wood and steel. Twelve dampers (6 steel and 6 wood) were ramp loaded to failure at a rate of 0.5 in/min. Test results showed that the failure mechanism was a shear failure of the material at strains > 500%, as shown in Figure 2. There was no delamination of the VE from the wood in any specimen. Six double lap dampers were subjected to 10 sinusoidal cycles at various displacements and frequencies. Replicate steel and wood dampers were tested. Comparison of the hysteresis loops showed that there was no difference in stiffness or energy dissipation capacity between the dampers constructed with wood and steel (Lewicki and Dinehart, 2000).

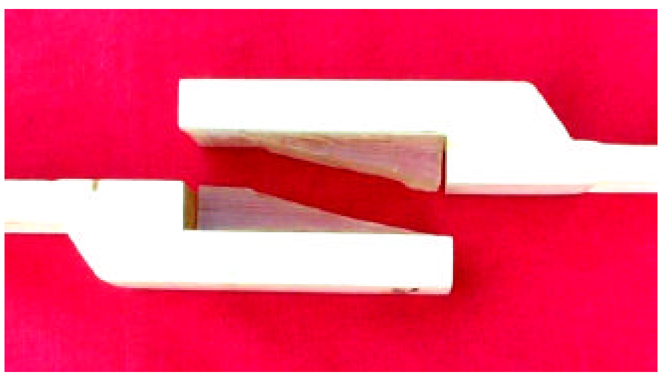

Figure 2: Typical failure mechanism of static test specimens.

Dinehart et. al., (2004a) conducted cyclic testing on standard nailed plywood to sheathing connections and on connections with one layer of VE material between the sheathing and the stud, as shown in Figure 3. Results showed that one layer of VE material, 0.005" thick, improved the energy dissipation capacity of the standard connection by over 30%. A preliminary full-scale test was conducted on an 8' x 8' shear wall with VE-sheet material sandwiched between the stud frame and sheathing. Figure 4 shows a comparison of this single test to conventional walls. It is clear from this figure that the improvements demonstrated in the connection translated to the full-scale wall. The average percentage increase in energy dissipation capacity was 26% at 0.71" of wall displacement. This percentage increase was typical for wall displacements ranging from 0.5" to 1.25". Similar to previous damped wall tests the VE-sheet material provided a constant source of energy dissipation. Connection testing is being continued to quantify the effect of moisture on this connection and to optimize the type and thickness of the polymer (Dinehart et. al., 2004b). Full-scale testing will commence upon completion of the connection phase.

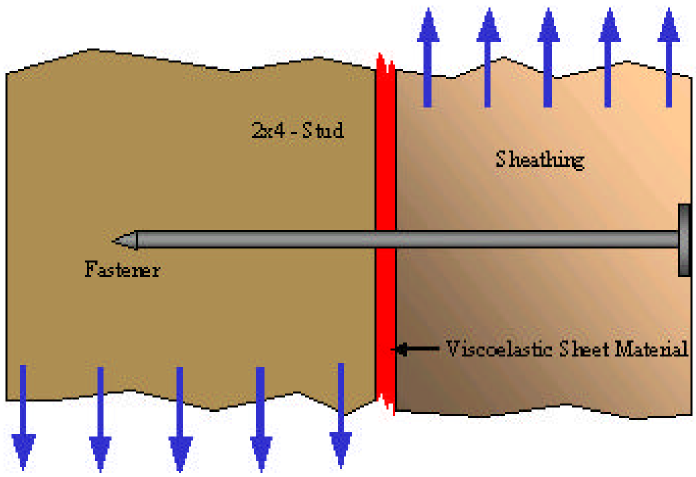

Figure 3: Schematic of VE material connection test specimen.

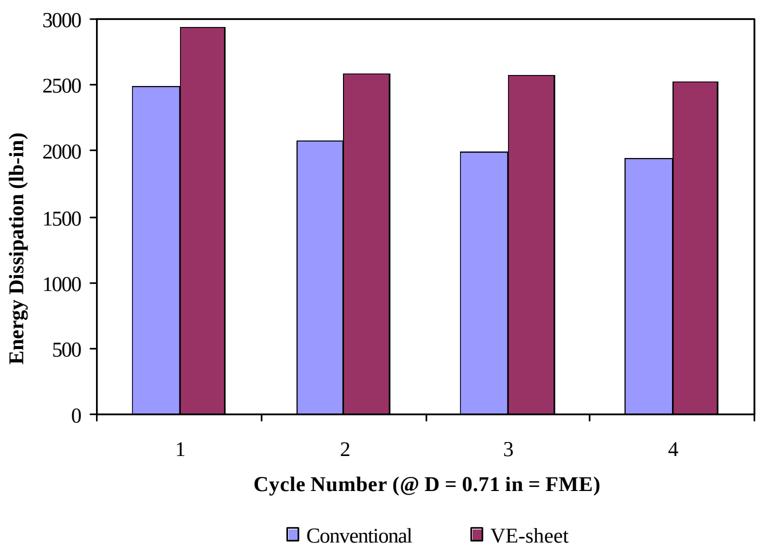

Figure 4: Comparison of the energy dissipation of conventional and VE-sheet shear walls.

Future Work

In search of solutions aimed at reducing recurring losses from natural hazards, the Institute for Business & Home Safety (IBHS) and the American Society of Civil Engineers (ASCE) convened a workshop in June of 2000, sponsored by the United States Department of Housing and Urban Development (HUD), the United States Geological Survey (USGS) and the USAA, an insurance and financial enterprise, and a member of the IBHS. ASCE (2001) provided a list of ten solutions sets and assigned priorities for six kinds of natural hazards. The three solution sets for earthquakes are provided below.

1. The highest priority should be given to research and development of mitigation measures that provide a continuous load path and increase the lateral resistance of the structural system to ground shaking.

2. High priority should be given to improving methods for increasing the energy dissipation capacity of the structural system, anchoring the house to the foundation, securing mechanical equipment and contents, and preventing house-chimney interaction and foundation failure.
3. Research on new and emerging technologies should be continued and accelerated, with a focus on active and passive energy dissipation devices, soil remediation techniques, and composite materials.

Each of the supplemental damping systems discussed previously can provide a solution to all three of these priorities. These systems provide a constant source of energy dissipation; thereby, improving the durability of a structure subjected to seismic loading. But in addition to investigating the energy dissipation characteristics, it is imperative to consider the practical aspects of design and construction.

The following strategy is suggested for continued research on supplemental damping in wood structures.

1. Passive Energy Dissipation Systems: Although the studies reviewed do not discuss specific costs of the system, it appears that the supplemental damping options discussed are cost effective when considering life-cycle costs of wood structures; however, the costs of these systems must be examined carefully. In their current forms, active damping systems and base isolation systems are too complex and cost prohibitive for mainstream application to wood structures. The literature clearly shows that most of the work to date has focused on VE material and fluid damper systems. Both systems have shown significant promise. It is suggested that future work continue to be focused on VE and fluid systems; however, the limited work done on hysteretic and friction dampers indicates that future research in these areas is also warranted.

2. Panelized Construction: Application of traditional dampers (VE, friction, viscous, and hysteretic), in diagonal braces have limitations due to connection issues and construction problems of fitting the brace and damper within the confines of the wall. Consequently, these traditional systems should be applied to panelized construction. Continued work at innovative solutions such as the VE sheet material or other types of polymers should be expanded to include the attachment of non-structural finishing elements such as gypsum.

3. Retrofit: Research should be aimed at the incorporation of these systems such that they can be used for retrofitting existing structures and traditional construction. Research should be conducted to investigate the possible use of Passive Energy Dissipation (PED) devices as hold-downs for wood structures. Conventional hold-downs are already integrated into the lateral load resisting system of wood structures. These PED hold downs could easily be used in panelized construction, but would also provide the added benefit of on-site installation by low skill labor for both retrofit applications and new construction.

4. System and Component Analysis: It is imperative that future work be aimed at the overall system performance. Any and all investigations should include both numerical and experimental work and should be performed at the component level (wood connections and shearwalls and supplemental damping elements), as well as the system level (full-scale structure). Analyses and testing should include static, cyclic, and shake table testing when possible.

5. Collaboration: Due to the relatively small number of active researchers in this area, it would seem prudent for them to work together as a team to form a cohesive plan to forward the implementation of supplemental damping schemes in wood structures. Additionally, due to the limited resources of the agencies (National Science Foundation, PATH, United States Department of Agriculture, CUREE) that have funded some of the research reviewed, it may be beneficial if a partnership is established between these organizations to support this specific research agenda.

6. Other: Based on previous research and recommendations by CUREE (2002a), future research should include an evaluation of the effects of construction tolerances, wall finish materials, hold-down devices, and moisture. Research on supplemental damping of wood structures should take into account recent research conducted on the structural effects of finishing materials (CUREE, 2002b) and anchorage devices (CUREE, 2002c), as well as the work being conducted in the area of wind resistance. From a design perspective the distribution of the systems, both vertically and horizontally should be optimized and a simple design and analysis procedure be prescribed. Finally, all studies should include a life-cycle cost analysis of the supplemental damping system.

Conclusion

Woodframe structures experience significant structural and nonstructural damage during earthquake events. Research aimed at developing supplemental damping schemes for woodframe structures will benefit society at large by providing a cost-effective advanced panel system that will reduce the damage, human injury and economic loss associated with woodframe structures in areas of high seismicity. The rationale for this course of study is that the seismic performance of low-rise structures can be significantly enhanced through the use of PED systems in wood structures. The past fifteen years has seen an explosion in the application of innovative systems and materials for natural hazard mitigation of the infrastructure. The research into these technologies has concentrated almost exclusively on their use in steel, concrete and masonry structures. The benefits of these advanced systems need to be investigated and exploited in woodframe construction.

These innovative applications of viscoelastic material and other supplemental damping technologies have the potential to profoundly impact the design, construction, and rehabilitation of woodframe structures. The potential improvements in performance will have a direct impact in reducing the structural and nonstructural costs of damage in woodframe structures. These improvements and the attendant dramatic cost savings can only be realized through innovative numerical and experimental research.

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