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DAMAGE-FREE SEISMIC RESPONSE OF MULTI-STORY TIMBER-STEEL HYBRID STRUCTURES WITH SUPPLEMENTAL DAMPERS

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Abstract

Timber-steel hybrid structures combine a steel frame with timber infill walls to create an efficient lateral load resisting system. Timber infill walls however, suffer damage, sustain residual deformations during major earthquakes, and therefore require extensive repair or even replacement if the cost of repair is prohibitive. In this contribution, it is examined if the use of supplemental dampers can protect timber walls from early damage and dissipate energy during earthquakes to control the seismic response. To this end, a simple novel timber-steel hybrid structure system with supplemental dampers is first described. This system, relies on the response of a conventional flexible steel frame to provide an elastic restoring force and on hysteretic energy dissipation devices that are installed between the steel frame and timber shear wall to control the seismic response while eliminating all damage to the shear walls. A case study of a 4-story building incorporating this novel concept is designed using the P-Spectra method and the Chinese code and then its response is investigated numerically. Nonlinear time-history analyses under a suite of seismic records scaled to 4 different hazard levels, i.e. minor, moderate, major and extreme is done numerically using the OpenSees modeling platform. Results show that the damped system has a more uniform inter-story drift distribution, attracts less seismic load, and has smaller displacement response. Dampers are able to dissipate energy instead of the infill walls and protect the wall from unrepairable damage. The residual deformation of the damped system is also smaller than the undamped damaged system after extreme earthquakes.

Keywords: timber-steel hybrid; seismic behavior; hysteretic dampers; wood-steel connection; nonlinear time-history analysis.

1. Introduction

The push for green / sustainable buildings has led to greater use of wood as a construction material worldwide. Many research projects have focused on the structural performance of mid-rise timber buildings in the past three decades. Despite its immense population and the need for more sustainable buildings, China still has restrictions limiting wood structures to only three stories because of fire safety issues. As such, hybrid wood-steel structures represent a promising new alternative for expanding the use of wood construction to mid-rise buildings. Since the self-weight of this kind of structure is reduced due to the use of wood assemblies, timber-steel hybrid buildings usually attract smaller lateral seismic forces, and the proportion of combustible construction material (i.e. wood) that is used in such buildings is reduced as well.

Research has been carried out recently on steel moment-resisting frames that are combined with wood-frame diaphragms [1][2]. Light wood-frame shear walls are used as infills in steel moment-resisting frames forming the lateral load resisting system (LLRS) of the structure. Previous experimental studies revealed that the installation of the infill wood-frame shear wall resulted in a significant increase in the initial lateral stiffness of the steel moment-resisting frame. However, as damage accumulates in the infill wood-frame shear walls under large inter-story drifts, seismic loads are increasingly resisted by the steel moment-resisting frames. This leads to greater inter-story drifts and enhanced overall damage to the structure. In addition, residual deformations and extensive wide spread damage of the wood shear walls implies large repair costs that can potentially require the demolition of the structure even if it has not collapsed. Fig. 1 illustrates some of the damage that was observed in full-scale tests under pseudo-dynamic loading. This includes mainly nail shear failures, damage to the sheathing and large permanent rotations of the sheathing [2].

(a) Nail shear failure

(b) damage on sheathing edge

(c) Large sheathing rotation

Fig. 1 Damage to timber infill walls during a full-scale testing

In order to limit the damage to the infill wood-frame shear walls, as well as to improve the overall seismic performance of this novel hybrid structural system, especially under major earthquakes, supplemental dampers are incorporated into the connections between the steel frame and the infill wall. The connections are designed to have enough stiffness and capacity to transfer shear force between the wood and steel up to the elastic load-carrying capacity of the infill wall. At a predetermined activation level, the supplemental dampers are activated, providing energy dissipation, and protecting the infill walls from damage.

In this paper, the concept of designing hybrid steel-wood systems with supplemental dampers is first presented, and the seismic response of a prototype 4-story structure with and without the supplemental dampers is investigated numerically. Inter-story drifts, residual drifts, story accelerations, base shear, and energy dissipation are discussed based on the analytical results. Recommendations on the application and design of the damped wood-steel connections for the timber-steel hybrid structure are then proposed.

2. Timber-steel hybrid building system with supplemental dampers

A damped timber-steel hybrid building system is investigated in this paper. Steel moment-resisting frames are combined with wood diaphragms and wood shear walls. Supplemental dampers are incorporated into the connections between the steel frames and wood shear walls. A thin concrete layer is also cast atop the wood diaphragm making it rigid enough to act as a rigid diaphragm. The hybrid system is mainly used in mid-rise structures, in which shear deformations dominate the lateral response of the system and story flexural deformations can be neglected. The conceptual behavior of this hybrid damped building system is illustrated in Fig. 2. At low lateral loading levels (Fig. 2a), the supplemental damper is not yet activated, and therefore acts as a connection element between the wood shear wall and the steel frame with large stiffness. The steel moment resisting frame and the wood shear wall deform together to resist lateral forces and provide a high stiffness for wind loading and low amplitude seismic loading (Fig. 2b). As the applied lateral the force increases, when the wood shear wall reaches a load that is approximately 40% of its capacity, which is considered as the onset of yielding in the shear wall, the supplemental damper is activated, i.e. sliding initiates (Fig. 2c). After this point, even though the inter story drift keeps increasing, the applied forces and deformations in the wood shear wall cease to increase, and remains in the elastic response range. The wood infill wall is therefore protected even under very severe seismic loading. In this system, the dampers dissipate earthquake energy instead of the wood infill walls. If the lateral deformation keeps on increasing to a point where the lateral stability of the system is threatened, the damper is designed to lock when the tensioning elements reach the end of pre-defined slots inside the damper. When this occurs, the wood shear wall is engaged, increasing the stiffness and the strength of the hybrid steel-wood frame (Fig. 2d) and further protecting against collapse as damage is induced in the shear wall. Only under such extreme loading conditions, would the wood infill walls have to be repaired or replaced. Typical hysteretic response curves for wood shear walls and supplemental dampers are shown in Fig. 3.

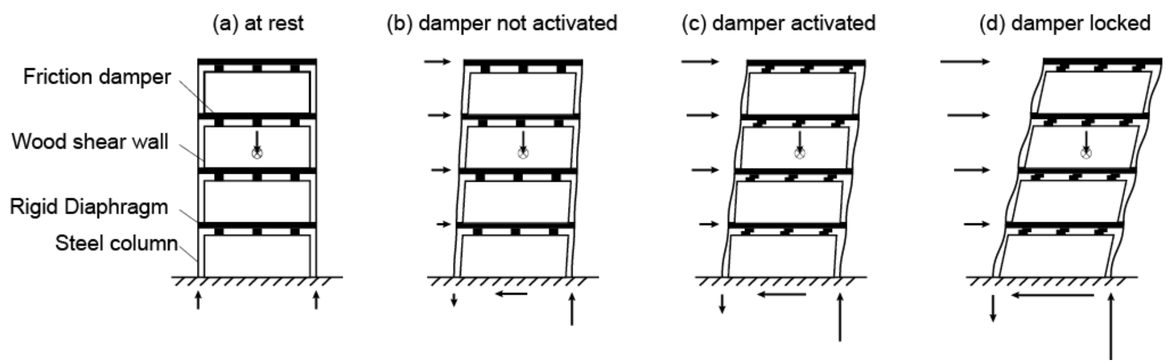
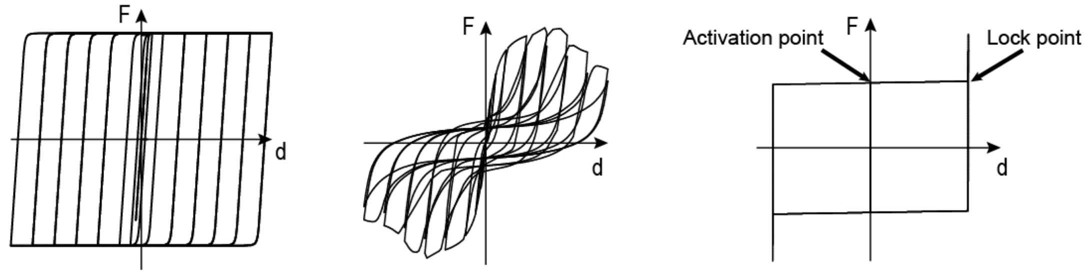


Fig. 2 Timber-steel hybrid building system with supplemental dampers (a) at rest (b) damper acts as a rigid connector (c) damper is activated (d) damper locks for extreme loading condition



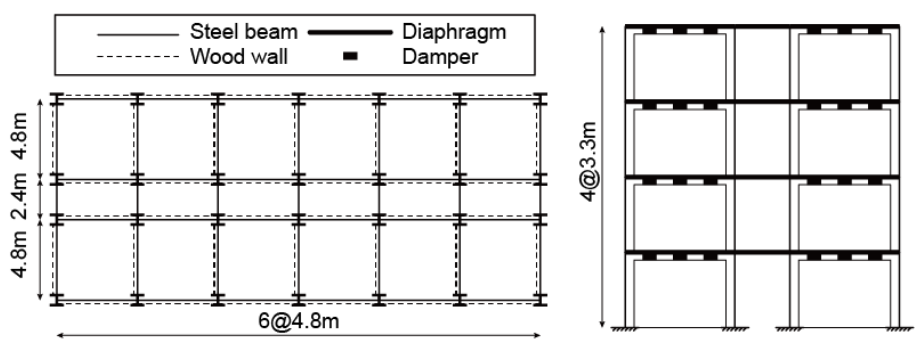
(a) Hysteretic curve of steel frame (b) Hysteretic curve of wood wall (c) Hysteretic curve of supplemental damper

Fig. 3 Typical Hysteretic curves

3. Overview of building design

3.1 Layout of a 4-story building with timber-steel hybrid building system

The structure discussed in this paper corresponds to a 4-story-3-span-6-bay structure located in the high seismic region of Sichuan Province in China. Fig. 4 shows the floor plan, elevation, and load data. The preliminary design of the steel members was based on an elastic analysis of the whole structure during a minor earthquake according to the Chinese code specification. Wood infill walls are considered as diagonal elastic springs with stiffness twice the stiffness of steel frame, according to [2].



Plan view

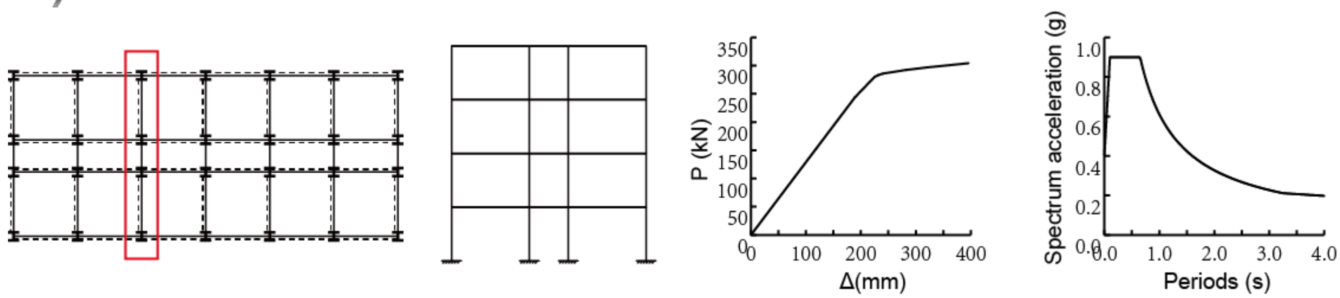
Elevation view

Dead load:
Floor: 1.9kN/m^2
Roof: 1.8kN/m^2
Inner wall: 1.8kN/m
Outer wall: 1.9kN/m
Live load:
Room: 2.0kN/m^2
Corridor: 2.5kN/m^2
Roof: 0.5kN/m^2
Snow: 0.5kN/m^2
Earthquake:
Seismic precautionary intensity: VIII(0.2g)
Site classification: type III, class 2

Fig. 4 Layout of building studied

3.2 Preliminary design of steel frame and wood shear wall

The P-Spectra (Performance-Spectra) method is employed to design wood infill walls and supplemental dampers. P-Spectra are graphic tools that relate the responses of nonlinear SDOF systems with supplemental dampers to various damping parameters and dynamic system properties that structural designers can control [3]. One representative planar steel frame in the y-direction as shown in Fig. 5(a)(b) was studied to define the properties of the dampers. The pushover analysis response of this frame is shown in Fig. 5(c). The target design spectrum is illustrated in Fig. 5(d), which has a probability of exceedance of 2% in 50 years, meeting the requirement of the major earthquake spectrum in the Chinese code. Eigenvalue analysis results on the bare planar steel frame were used to obtain the structure's modal periods and mode shapes. These results are the input parameters of the P-spectra.



(a) Planar frame from prototype (b) Planar steel frame (c) Push over result (d) Target spectrum

Fig. 5 Planar frame studied in P-Spectra method

Using the P-Spectra method, the distribution of the hysteretic dampers was defined [4]. The initial stiffness of both wood shear walls at each floor was assumed to be 15kN/mm for the first and second floors, 10kN/mm for the third floor and 5kN/mm for the fourth floor, respectively. Two identical shear walls are set in each story, so the initial stiffness of a single shear wall would be designed to be 7.5kN/mm, 7.5kN/mm, 5kN/mm and 2.5kN/mm respectively. The activation load of the dampers for each story was set to 80kN, 140kN, 95kN and 20kN, respectively, which means the elastic ultimate strength of the wood shear wall should not be smaller than 40kN, 70kN, 47.5kN and 10kN, respectively in each floor. The design of wood shear walls was carried out by following these stiffness and strength values and using previous design recommendations [2].

3.3 Design of supplemental dampers

Friction dampers were identified as the most desirable choice for this hybrid structure by examining the P-Spectra, for different damping systems. The detailed design of the damper is illustrated in Fig. 6. The main components are inner T steel panel, outer L steel panel, specialized friction material, and bolts. The main friction interface is between the friction material, which is embedded to the inner T steel, and the outer L panel. A 130 mm slot was included in the inner panel, with this length being defined using the performance targets specified in the Chinese code. The activation load is controlled by the pre-stress of the bolts which connect the inner panel and the outer panel together. Previous work [5] has quantified the relationship of bolt load to friction coefficient. So by controlling the torque value when fastening the bolts, the activation load of the damper can be closely predicted. The initial and post-lock stiffness of the damper is calculated as the total shear stiffness of the inner and outer panels. The connections of the damper to the steel frame and wood shear wall are designed conservatively that they have larger shear capacity than the wood infill walls.

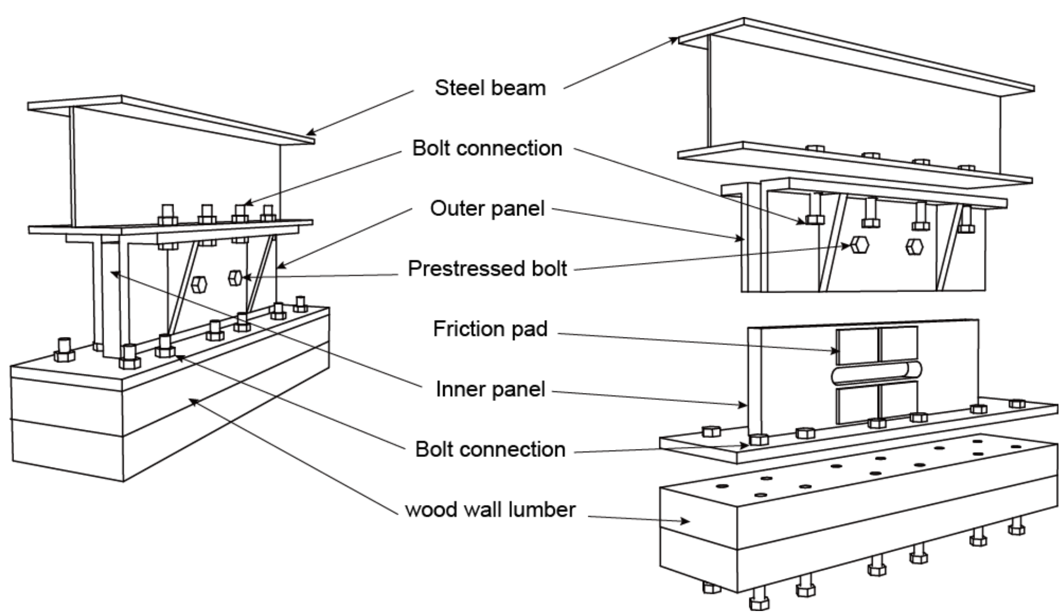


Fig. 6 Design of damper

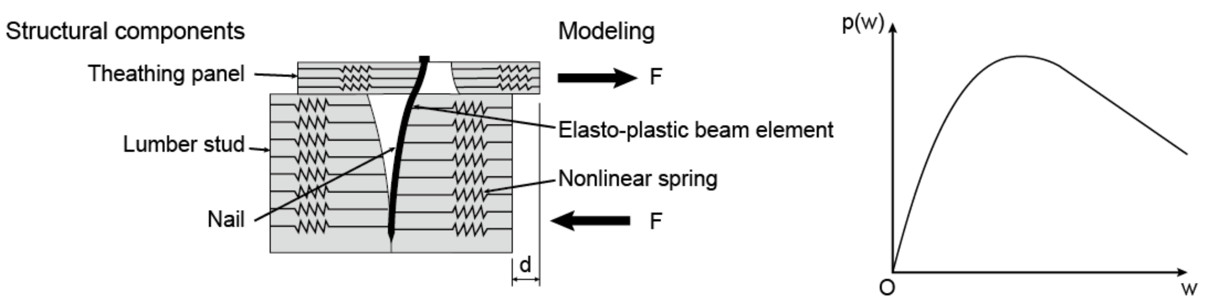
4. Numerical modeling approach

4.1 Assumptions

A numerical model of the hybrid structure system with supplemental dampers was created to capture its behavior under cyclic loading. The main focus of the numerical study was to obtain the shear force distribution between the steel frame and wood infill wall for the conventional hybrid steel frame, and to compare the seismic behavior of the hybrid system with and without supplemental dampers. As is mentioned above, a layer of concrete is installed on the wood diaphragm to improve the out-of-plane stiffness and provide sound-isolation. Therefore, the lateral stiffness of the diaphragm is large enough that it can be modelled as a rigid diaphragm. In this way, there are only 3 degrees of freedom on each floor. Steel columns and beams are connected using high-strength pre-stressed bolts, so the connection can be assumed as rigid or near rigid, and are therefore modeled as rigid joints in this study. The infill wall has a large in-plane stiffness, but a very small out-of-plane stiffness, so it is conservatively assumed in the numerical study that it has zero out-of-plane stiffness.

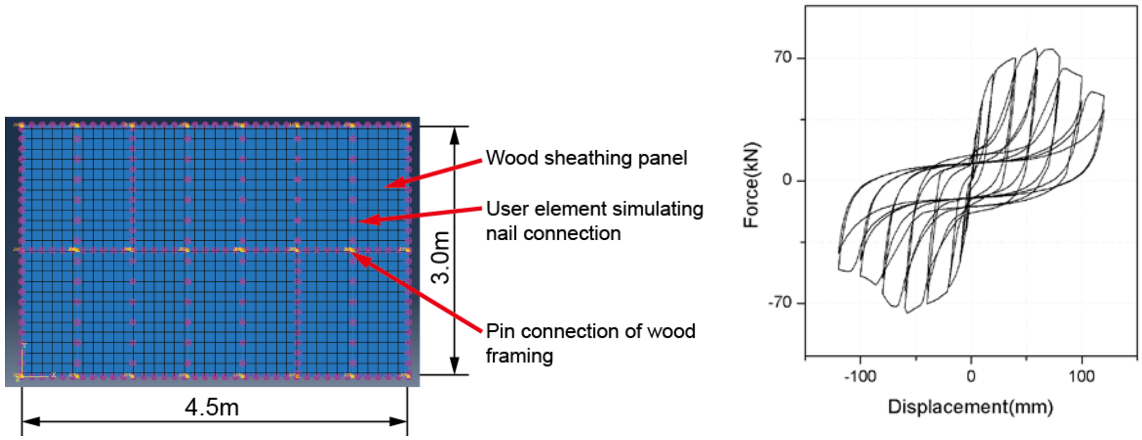
4.2 Modeling of wood infill walls

Wood infill walls consist of lumber frames and OSB sheathing panels connected by nails. The main characteristics of the wood infill wall is governed by the connection properties. In previous studies [6], a model for simulating the hysteretic behavior of nails embedded in wood has been developed. In this model, a nail is meshed to elasto-plastic beam elements, interacting with surrounding wood with compression-only springs, as illustrated in Fig. 7(a). The force-displacement relationship of these springs is shown in Fig. 7(b). In this modeling approach, the hysteretic force-displacement relationship of the nail is obtained by finite element analysis. This relationship can be simplified as a uniaxial force-displacement relationship that represents the behavior of the nailed connection. In a detailed 2D shear wall finite element model, two orthogonal uniaxial nonlinear springs are used to represent a nail connection. The direction of each of the springs are set to be parallel and perpendicular to the initial rotation angle respectively. The detailed model is set up in ABAQUS as illustrated in Fig. 8(a). In this way, the hysteretic behavior of a planar wood shear wall can be simulated with good accuracy [1]. Because of the rigid diaphragm assumption, the rotational displacement is ignored, so that the shear wall can be represented by a uniaxial single degree of freedom representing the relative deformation of the top point to the bottom point of the shear wall. A hysteretic relationship obtained from an ABAQUS model of this type is shown in Fig. 8(b).



(a) Modeling nail connection (b) Modeling embedment behavior

Fig. 7 Modeling hysteretic behavior of nail in wood

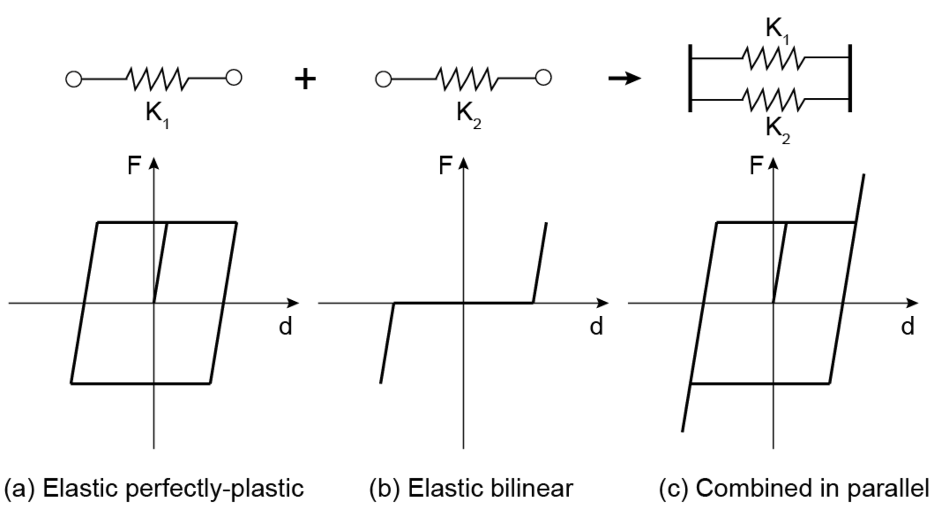


(a) 2D shear wall finite element model (b) force-displacement relationship of one timber wall

Fig. 8 Modeling timber infill wall

4.3 Modeling of supplemental dampers

For supplemental dampers, there are mainly four characteristics to be simulated, i.e. initial stiffness, activation load, locking of the device, and post-locking behavior. Before the damper is activated, the frictional force provides a rigid connection which makes the inner panel and outer panel deform together, and the panels remain elastic. So an elastic force-displacement behavior with this high initial stiffness is considered in this stage. The stiffness is calculated as the total shear stiffness of the inner and outer panels. When the damper is activated, the force remains constant at the activation load, while a large displacement occurs. The first two stages of the behavior can be simply simulated by an elastic-perfectly plastic uniaxial material. For the third stage, locking of the damper occurs when the bolt reaches the edge of the slot in the inner panel in either direction At this stage, if the external excitation keeps on increasing in the same direction, slipping no longer occurs, and the stiffness of the damper becomes similar to the initial stiffness. As the force increases, shear failure of the bolts or bearing failure within the slot may occur, but this should be avoided by ensuring that sufficient strength is provided to ensure that the resistance against these failures is greater than the shear strength of the wood infill wall, such that the wood wall is expected to fail before the damper does. To simulate all the features of the damper, two uniaxial springs, an elastic-perfectly plastic spring (Fig. 9(a)) and a multi-linear elastic spring (Fig. 9(b)), were combined in parallel. The combined hysteretic curve is shown in Fig. 9(c).



(a) Elastic perfectly-plastic (b) Elastic bilinear (c) Combined in parallel

Fig. 9 Modeling of friction damper

4.4 Finite element model of the entire building

A 3D numerical model of the building studied was then created using the open source modeling platform OpenSees. The building consists of three parts mainly, i.e. a steel frame, wood infill walls, and supplemental dampers. Rigid diaphragm constraints are constructed on points of the same floor to simulate a rigid diaphragm. Elastic-perfectly plastic uniaxial springs are chosen to model the constitutive law of the steel material. The steel sections are meshed into fiber sections and aggregated with shear and torsional stiffness. Force-based beam-column elements with 5-point Gauss-Lobatto integration is used to simulate steel beams and columns. For the wood shear wall, the SDOF force-displacement relationship mentioned above is calibrated using the Pinching 4 uniaxial material. The calibration result is shown in Fig. 10. There are mainly four stages of deformation in the wood infill wall. The first stage is a near elastic range where the stiffness has very limited degradation. In the second stage, plastic deformations occur, but the infill wall still maintains a large potion of its stiffness without strength degradation but with some pinching. At the third stage, which corresponds to large deformations, the stiffness degrades sharply, with severe pinching in the hysteresis caused by severe damage to the shear walls. At the fourth and final stage, the strength of the wall decreases rapidly and the wall is completely damaged. The damper is modelled as a nonlinear spring using an elastic-perfectly plastic uniaxial material combined with a bilinear uniaxial material in parallel as is mentioned above. The wood shear wall model and damper model are connected in series to form a wall-damper nonlinear spring, capturing the force-displacement relationship of the axial degree of freedom in a two node link element, oriented in the x-axis, which is parallel to the shear loading direction of the infill wall. The diaphragms are connected using two node links, each of which represents a wall-damper pair, as illustrated in Fig. 11.

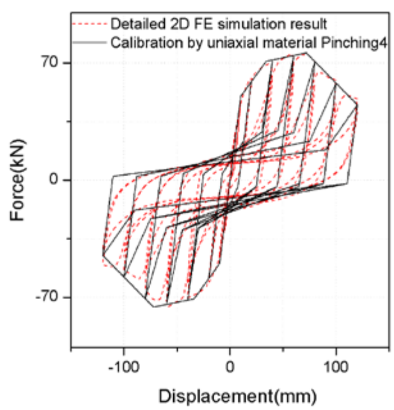


Fig. 10 Detailed numerical analyses used to calibrate spring nonlinear elements

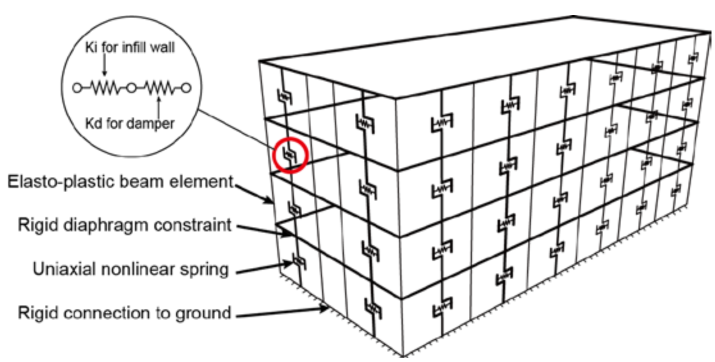


Fig. 11 modeling entire building

4.5 Nonlinear time-history analysis

10 records were selected and scaled in order to match the design spectrum provided in the Chinese code. Preliminary analysis showed that the natural period of the bare steel frame was 1.15s, and the natural period of the hybrid system was 0.57s. So the records were scaled for the period range of 0.57 s–1.15s using a two-step

scaling procedure. The first step was to set a scaling factor for each of the records in order to make the SRSS of the error for every meshed point in the selected period range on the spectrum to the target spectrum the smallest. Then, a second factor was applied to the entire scaled suite, to make the average acceleration spectrum every meshed point larger than the target spectrum in the target period range. The final scaling factor is the product of these two factors. Four suites of records were considered, representing minor earthquake, moderate earthquake, major earthquake and extreme earthquake hazard levels respectively. The spectrum acceleration plateaus were specified to be 0.16g, 0.45g, 0.9g and 1.2g, respectively. Fig. 12 shows the acceleration spectrum of the scaled record suite for the major earthquake hazard level as well as the target code-defined spectrum. Inherent damping was modelled as 5% Rayleigh tangent stiffness damping according to [1]. A Krylov-Newton algorithm was used with analysis time step of 0.001 seconds. The excitations are only applied in the y-direction, because the seismic behavior is primarily studied in this direction.

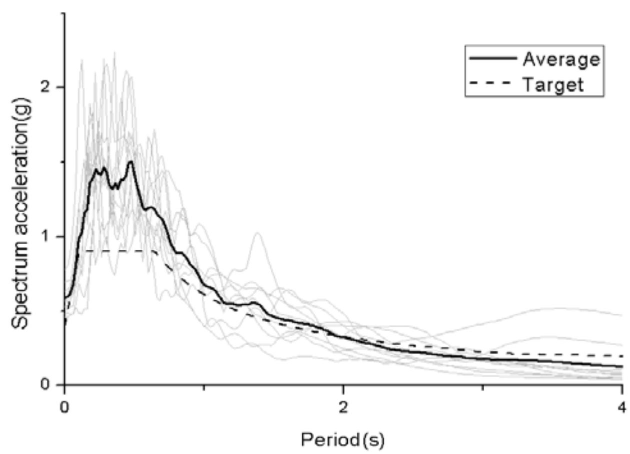
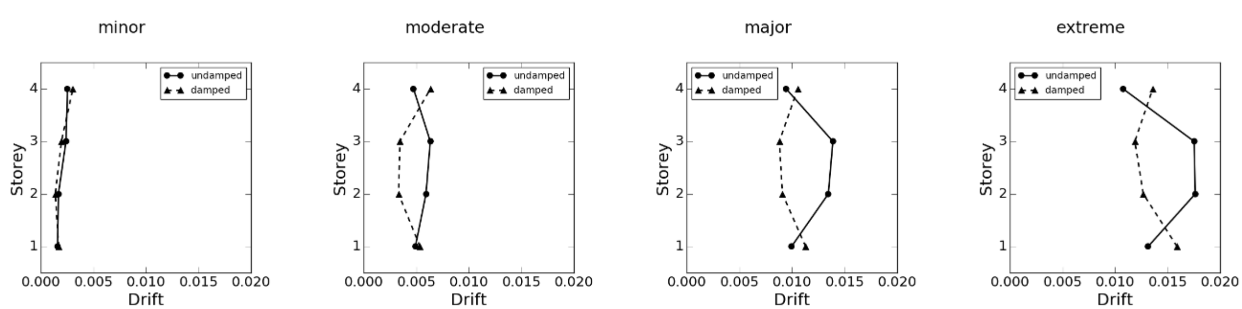


Fig. 12 Record suite spectrums compared with target spectrum

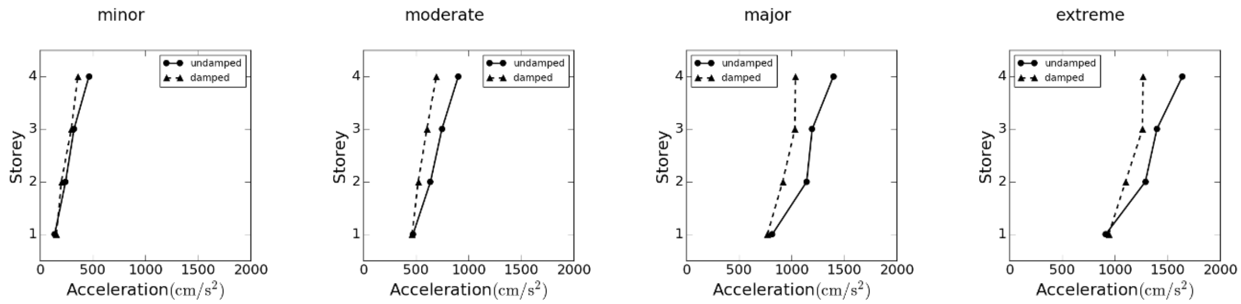
5. Results and discussion

Fig. 13(a) shows the mean inter-story drift for each story, under the four suites of seismic excitations. The inter-story drift of different stories varies significantly for the undamped system. This is due to the different inter-story stiffness at each level. The stiffness of the fourth story is larger than the lower stories, because the steel sections are limited to larger sections by slenderness requirements included in the Chinese code. The damped system has a more uniform inter-story drift distribution along the elevation of the structure. Fig. 13(b) illustrates the acceleration distribution. The acceleration for most stories of the damped system is lower than the undamped system by about 20%. This means that the dampers achieve a reduction in the seismic force that is applied to these timber-steel hybrid structure. Fig. 13(c) shows the mean displacements for each story, illustrating that the dampers also reduce the overall drift response of the hybrid structure.

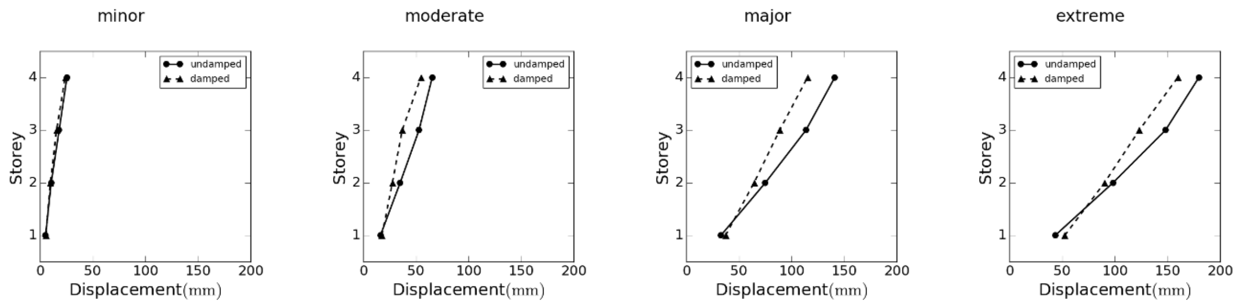


(a) Inter-story drifts for each story

Fig. 13 Mean inter-story drift, acceleration and displacement (to be continued)



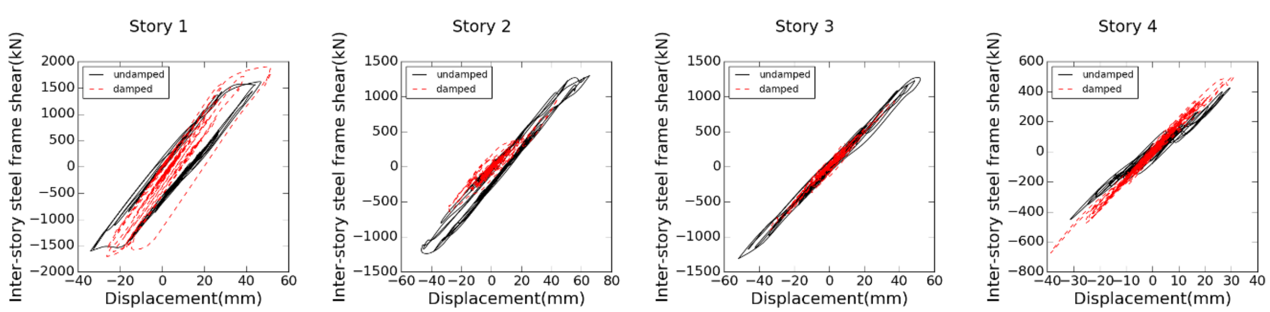
(b) Accelerations for each story



(c) Story Displacements

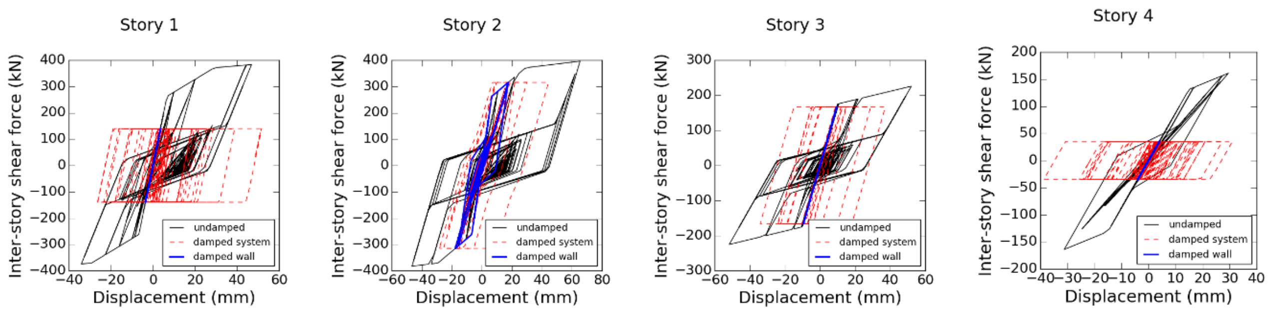
Fig. 13 Mean inter-story drift, acceleration and displacement

Fig. 14(a) and Fig. 14(b) shows the shear force-displacement relationship of the steel frame and the infill walls, respectively, with and without the damping system under a particular major earthquake excitation (scaled Chichi earthquake record). It can be observed from the hysteretic curves of the steel frame that are shown in Fig. 14(a) that the steel columns on stories 2, 3 and 4 remained nearly elastic, while some limited plastic deformations occurred on the first story. The inclusion of the dampers didn't affect the inelastic response of the frame in any significant way. As for the infill walls in Fig. 14(b), the dampers had a considerable effect on their response. For the undamped system, the inter-story shear of the wood walls are illustrated in black curves, extensive plastic deformations were observed. A deformation corresponding to a severe damage state was reached, implying that the walls had suffered unrepairable damage. On the contrary, the hysteretic curve of the damped system showed that the peak force in the infill walls was limited by the dampers as expected, resulting in little plastic deformation, as is illustrated in blue curves. It is also observed from the red curves corresponding to the total inter-story shear of the wall-damper system that most of the energy were dissipated by the dampers in the damped system, while the main energy dissipation component was the infill wall for the undamped system.



(a) Inter-story steel frame shear – displacement response

Fig. 14 Shear force - displacement relationship and energy dissipation (to be continued)



(b) Inter-story infill shear – displacement response

Fig. 14 Shear force - displacement relationship and energy dissipation

Fig. 15 shows the displacement time-history of the roof level for the undamped and damped systems under a particular extreme seismic excitation (scaled Kobe earthquake record). At the end of the excitation at t = 20s, it appeared that the damped system had a larger residual displacement (17mm) than the undamped system, -4mm. This is due to the activation of the damper and its rigid plastic response, which does not re-center after activation (even though the elastic steel frame provides some restoring force). For the damped system, after the earthquake, the bolts of the dampers, which are accessible, can be released so that the elastic strain energy in the steel frame that is locked in by the damper resistance can be released to re-center the frame. At time 30s, the dampers were simulated to be removed from the deformed structure, and the structural response to this release of damper force can be observed in the figure. The residual displacement of the damped system is 0.9 mm (practically zero), smaller than the undamped system of -4mm, although this value is also very small. This shows that the damped system has near zero residual deformation and practically no damage to the steel sections or the wood panels, and therefore can be re-occupied with minor if any repairs immediately after this major earthquake.

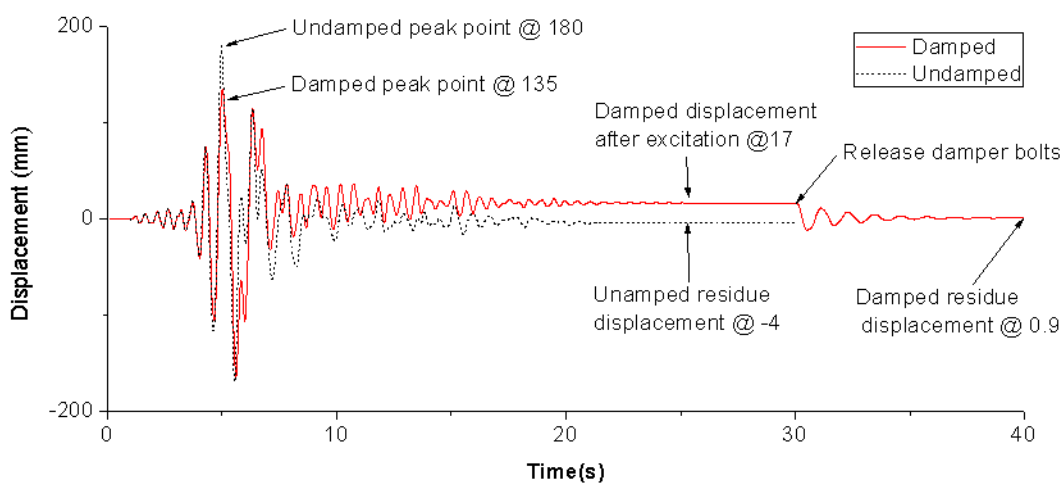


Fig. 15 Time history of roof displacement

6. Conclusions

A novel timber-steel structure system with supplemental friction dampers is presented in this paper. Friction dampers can prevent damage in the wood shear walls and can dissipate energy to control the seismic response. A 4-story building with such a system was designed and studied numerically. The preliminary design of the building was based on specifications in the Chinese code. The P-Spectra method was used on a planar frame to determine the design parameters for dampers and stiffness of the wood infill walls. A numerical model of the building system was then constructed in OpenSees. Wood infill walls were simulated by the Pinching4 material, and the dampers were simulated by an elastic-perfectly plastic spring and a bilinear elastic spring combined in parallel. The seismic behavior of the structure under minor, moderate, major and extreme hazard levels was then studied through non-linear time-history analyses.

The results show that the damped system performs better than the undamped system. The peak story acceleration of the damped system is smaller than the undamped system, indicating that the damped system attracts less lateral seismic forces. The inter-story drift of the damped system varies uniformly along the elevation, while the variation of the undamped system is larger. The displacement for each story of the damped system is also smaller than that of undamped system, and this while the seismic forces and accelerations at each floor are lower, thus improving the overall response of the structure. For the undamped system, the seismic energy is mainly dissipated by the wood walls. When the major seismic excitation is applied, unrepairable plastic deformations occur in the wood walls, which is costly and disruptive to repair or replace. For damped systems, however, seismic energy is mainly dissipated by the dampers while the wood walls have little plastic deformation, which indicates that no repair is required. Simulation results also demonstrated that the damped system has less residual deformation when the damper bolts are released after an earthquake compared to undamped system even though the undamped system also sustained small residual deformations.

The results presented in this paper, indicate that proposed damped system offers an interesting new alternative design that can protect the wood walls from unrepairable damage. Further research is recommended to optimize the design of the wood wall and dampers, to make the system even more efficient. The influence of diaphragm stiffness and steel joints also needs to be further investigated.

7. Acknowledgements

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