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Advanced Composite Multi-infill Panels for Seismic Retrofitting

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Summary

In this paper, a conceptual design, fabrication, and testing of the advanced Polymer Matrix Composite (PMC) infill system are presented as a seismic retrofit strategy. Such a system is designed to have multi–infill PMC panels with a passive energy mechanism. This system has two separate components – an inner PMC sandwich panel and outer damping panels. The interaction of these two components may produce considerable stiffness and enhanced damping properties in the structure at different drift levels. As part of this research, analytical and experimental studies were performed to investigate the effectiveness of the proposed multi–infill panel concept. The prefabricated multi–panel PMC infill holds great promise for enhanced damping performance, simplification of the construction process, faster implementation and reduced cost when used for seismic retrofitting applications.

Introduction/Motivation

In the United States, many older structures located in seismic zones lack strength and damping. One approach for correcting these deficiencies was the construction of infill walls to strengthen and stiffen the structure. As such, large numbers of buildings throughout the U.S. have structural frames infilled with unreinforced clay brick, concrete masonry, or structural clay tile. This infill construction has been prevalent since the late 1800's, and is still popular in moderate seismic regions of the central and eastern United States. However, sometimes cost, time constraints, or the need to limit disruptions to building operations may dictate that solutions other than cast–in–place construction be used. A new rehabilitation scheme is needed that will simplify the construction process; reduce time, cost and inconvenience of construction; and reduce the loss of functional use of a structure both during and after construction. Disadvantages associated with many of the traditional strengthening techniques have led researchers to develop innovative methods using advanced composite materials. The use of advanced composites for a variety of rehabilitating applications has been rapidly increasing in recent years. The main reasons for using composites are their superior strength–to–weight ratio, stiffness–to–weight ratio, and durability in corrosive environments as compared with conventional materials. Such benefits have the potential to conveniently and effectively aid in the mitigation of earthquake damage.

In this paper, the conceptual design of the multi–panel PMC infill system, composed of an inner PMC sandwich infill and outer FRP damping panels with passively combined interface damping layers, is proposed and tested to investigate its effectiveness as one approach to seismic retrofitting. The main scope of this research is focused on the shear deformation of both combined interface damping layers and the structural response of a steel frame infilled by the multi–infill PMC panels subjected to monotonic and cyclic loads.

Background of this Research

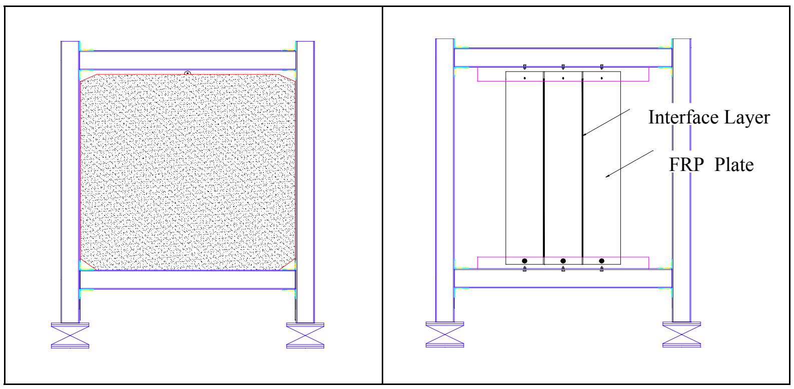
In the 1980's, the National Science Foundation (NSF) began to fund research on seismic rehabilitation. The objectives of the program were to provide information for evaluation of the vulnerability of existing structures at various levels of seismicity, and to develop advanced strategies for repair and retrofitting. Nonstructural rehabilitation was accomplished through replacement, strengthening, repair, bracing, or attachment. Recently, new rehabilitation approaches for critical facilities have been identified. Hospitals are classified as among the most important public facilities and are an important part in hazard emergency management. Hospitals are expected to provide uninterrupted and efficient medical services during and after an earthquake, or any natural hazard. As part of MCEER's research initiatives in the area of advanced analyses and protective technologies for seismic retrofit of critical facilities, FRP composite materials have been investigated as a new seismic strategy. The proposed methods may provide the solution to creating cost-effective and stakeholder-acceptable retrofitting strategies for maintaining functionality of critical facilities and their contents during earthquakes. As an innovative alternative, the lightweight FRP composite has the potential to emerge as an alternative material for non-structural elements, such as infill walls, that can be used as a seismic retrofitting strategy in regions of moderate to high seismicity.

Conceptual Design and Construction

The basic design philosophy and structural technique considered herein focuses on increasing the efficiency of retrofitting a structure before and after earthquake damage. The properties of the prefabricated PMC infill systems can be easily modified to suit their functional purposes. Fiber orientations and stacking sequence of the PMC materials can be adjusted to enhance structural behavior without any limitations imposed by existing configurations. Also, the ductile behavior of PMC infill systems can prevent catastrophic failure of the overall structure. From a construction point of view, PMC infill systems can be easily installed during the strengthening and retrofitting process of existing structures. A full–scale multi–panel PMC infill system was planned to test these parameters.

The proposed multi–panel PMC infill system is composed of two separate, basic structural components: an inner PMC panel and outer FRP damping panels. Figure 1 shows the geometric configuration of these basic structural components. The primary design concept of the proposed multi–panel PMC infill system emphasized two aspects; (1) enhancement of damping properties from the passive interface damping layers, and (2) providing considerable lateral stiffness by the PMC infill at high drift level to resist severe earthquake excitation, and avoid excessive relative floor displacements that cause both structural and non-structural damage. These two separate components, along with the steel frame, are intended to provide the desired stiffness or/and damping following different drift values.

For the inner PMC component, a sandwich type was considered to reduce the weight, sound, and vibration as well as to improve the structural rigidity of the composite wall. The PMC sandwich infill consisted of two fiber–reinforced polymer (FRP) laminates with an infill of Divinycell H–100 sheet foam in between. The Divinycell foam is a semi–rigid PVC used as a core material in conjunction with high–strength skins to produce strong, stiff, lightweight composite structures. As observed in previous research (Jung and Aref, 2003), the dominant failure of the PMC sandwich infill panel was elastic buckling under racking load. By considering the observed failure mode, an iterative process by numerous finite element simulations was carried out. The maximization of buckling loads with respect to laminate configuration was the objective function of the inner PMC panel design. Since the structural behavior of sandwich constructions is strongly affected not only by the types of fiber reinforced composite materials used, but also by the fiber orientations and stacking sequences of individual plies constituting the sandwich faces, the determination of optimum stacking sequence is a significant key parameter in the design process. By considering several stacking sequences, Figure 2 shows the maximum buckling force obtained from finite element analysis (ABAQUS 2000).



a) Inner PMC sandwich infill b) Outer FRP damping panel

Figure 1. Configuration of a multi–panel PMC infill system

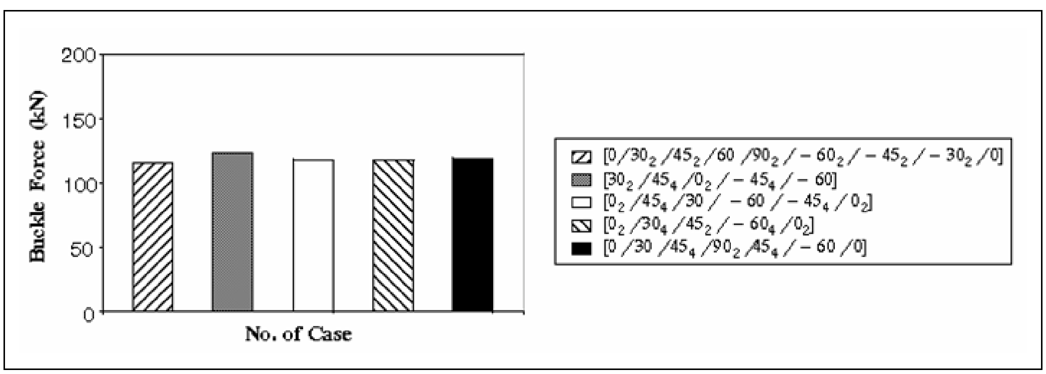
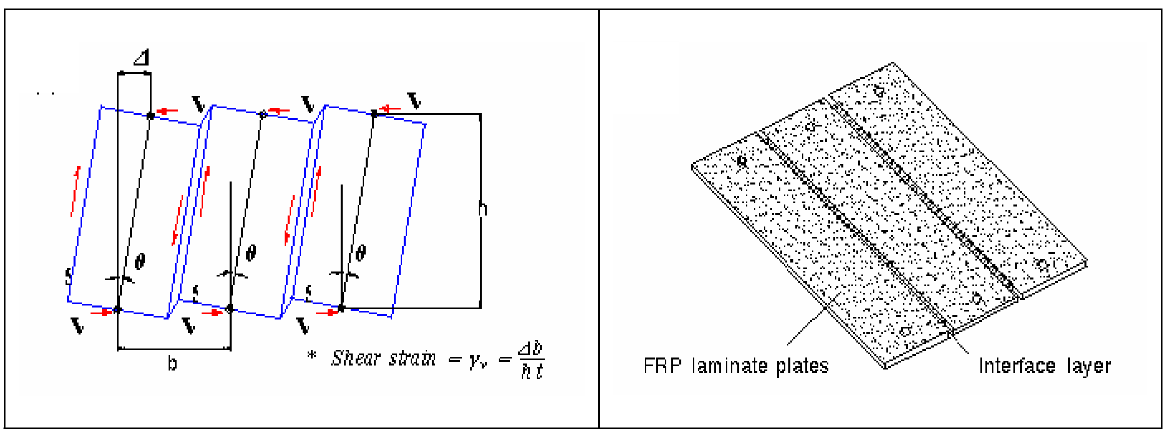


Figure 2. Results for maximum buckling force of applied fiber stacking sequences

For the steel frame with infills, the presence of gaps between the columns and the infill wall, and/or between the top beam and the infill wall, may be unavoidable. These gaps may negate some or all of the stiffness provided by the infill (Riddington 1984). In the design of the PMC sandwich infill, these unavoidable gaps between the infill and the opening of the steel frame can be used as the other design parameter to achieve the increased lateral resistance at specific drift. The post–action of the infill after allowing some amount of horizontal deflection would be expected to prevent excessive relative floor displacements. However, large gaps are not practically tolerable for pure infilled frame structures, because they are normally subjected to alternating loads. On the basis of previous results

(Dawe and Seah, 1989), it is assumed arbitrarily that the maximum designed side gap was allowed to have less than 0.4% of the infill dimensions, even if there is little decrease in the stiffness and/or strength of the infill action. By using finite element simulations to represent the PMC infilled frame with different side gap distances at the interface, the force–displacement response was evaluated. Finally, the contact target was designed in the range of 2% to 2.5% for lateral drifts to allow enough shear straining of the combined interface layers.

For the outer damping panel design, the passive damping panel concept of Gasparini et al., 1981 was adopted, with shear deformation of the interface layers between FRP plates along the relative motion of the top and bottom beams. These outer FRP panels were designed to achieve initial static stiffness and an acceptable maximum strain at the interface layers. The selected FRP laminate was made of the same materials used in the fabrication of the inner PMC sandwich infill, and the proposed interface damping layers consisted of two composite damping materials, such as 3M viscoelastic solid and polymer honeycomb materials. The basic concept of these combined composite damping materials was proposed by Jung and Aref (2003), and the enhanced damping property was observed by experimental and analytical studies. Practically, the proposed damping system could be used in as many panels as necessary to achieve different levels of damping and stiffness. In this study, by considering an optimum case relative to high material costs, the geometric configuration of the outer damping panels was determined to have three FRP laminate plates and combined interface damping materials at the interface between them as shown in Figure 3.



(a) Geometry of the deformed panels during inter–story drift (Gasparini et al., 1981)

(b) Fabrication

Figure 3. Design and construction of the outer damping panels

As a key design parameter of the combined interface damping layers, the design can be carried out for the required damping ratio of the structure. According to the required design damping ratio, the geometric size of the FRP plates, and the interface viscoelastic layer dimensions and properties can be determined by simple calculation. As shown in Figure 3a, an idealized symmetric motion was assumed; accordingly, the thickness of the FRP laminates was designed to have rigid body motion to make idealized shear deformation in the combined interface damping layers. That is, the laminate thickness could be determined from the maximum allowable interface deformation to insure the maximum shear strain in the viscoelastic materials. For the bonding effect of the interface layers, a perfect bonding was assumed. Therefore, the geometric size of the outer damping panels can be adjusted to the configuration of the combined interface damping layers. In this study, considering the natural frequency of the undamped structure, 5-10% increased damping was considered as a design target due to expensive viscoelastic material and limited experimental results. The selected mixing ratio of viscoelastic material was designed to have about 60% of total damper area, while the honeycomb material was used as the remaining portion of the combined damping layer.

Experimental Investigation and Results

In the experimental phase, testing of a steel frame with and without a composite infill wall was planned. In the experimental setup procedure, a steel frame with a PMC sandwich infill was tested first. Figure 4a shows a steel frame in which a PMC sandwich infill has been placed. The objective of this test was to investigate the in–plane response of the PMC infill when top and side gaps were allowed between the infill and the opening perimeter of the steel frame. Consequently, the outer damping panels were set up as shown in Figure 4b, and tested to evaluate the overall response of the multi–panel PMC infilled frame structure. Monotonic and cyclic loading was applied in the tests.

a) Steel frame with PMC sandwich infill　　　b) Steel frame with multi-panel infill

Figure 4. Experimental specimen setup

Testing of a Steel Frame with PMC Sandwich Infill

The purpose of this test was to investigate in–plane behaviors of the PMC sandwich infill along with preset initial top and side gaps. Figure 5a presents the numerical and experimental responses of the PMC sandwich infill panel with allowed initial gaps under push–over load. The force–displacement relationship obtained from the test clearly indicated that the contact point of the PMC infill with a 7.6 mm initial side gap was approximately 5.0 cm. Beyond that point, there is a progressive increase in lateral load resistance as the contact area increases. From the stress and strain outputs of the testing of the steel frame infilled with a PMC sandwich panel, the compressive strut angle for the infill was evaluated and compared with the numerical results (depicted in Figure 5b).

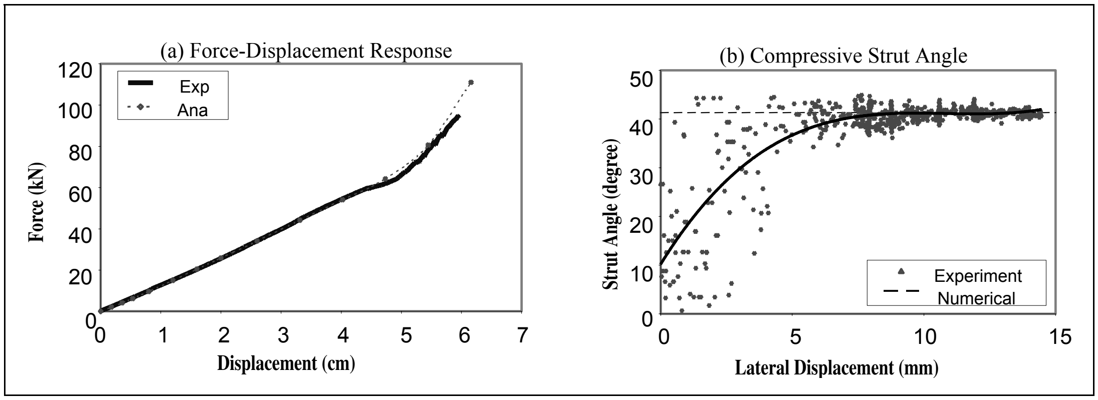


Figure 5. Results of steel frame with PMC sandwich infill (1.0% drift, push–over load test)

Testing of a Steel Frame with Multi–panel PMC Infill

Monotonic tests were conducted at 0.5%, 1.0%, and 1.5% drift. Important information about in–plane stiffness and the effect of the interface layer can be obtained from such experiments. As shown in Figure 6a, the measured overall stiffness of the multi–panel PMC infilled frame was larger than that of the steel frame. It is evident that the interface layer increased the lateral resistance by the contribution of the viscoelastic materials. However, the stiffness of the multi–panel PMC infilled frame was found to vary from 0.96 kN/mm to 1.35 kN/mm after allowing 0.8 cm of lateral displacement during the test. In the fabrication, bolt holes of each connector between the outer FRP panels and the steel beams were made 0.125 inches larger than the bolt shaft diameter. As such, there was a slippage between the bolt shank–to–bolt holes until the pin or slot connector is locked in place. Once a desirable locking configuration is achieved, the interface layer will be subjected to shear force. Figure 6b presents the shear deformation of the interface layer after locking the connectors.

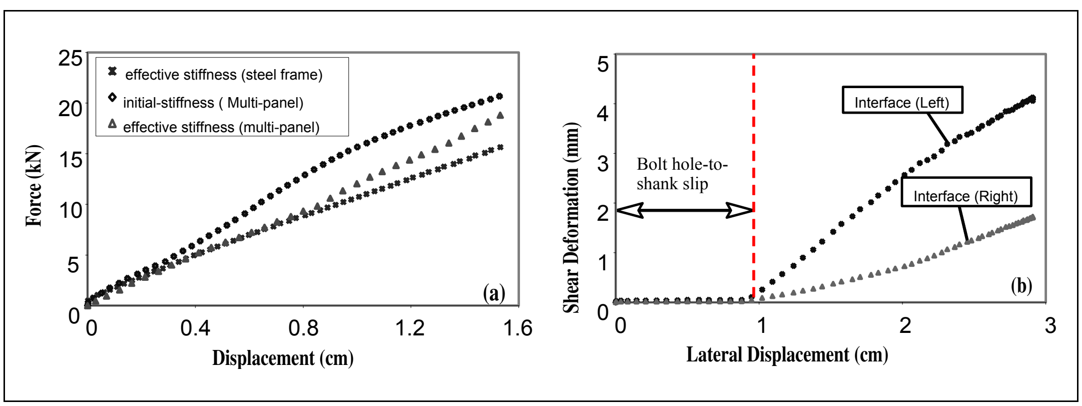


Figure 6. Results of steel frame with PMC sandwich infill (1.0% drift, push–over load test)

Finally, the energy dissipation that existed in the multi–panel PMC infilled frame was investigated. Generally, the overall damping exhibited by a structure arises from many sources, such as cyclic straining of structural and nonstructural elements, friction at interfaces, and nonlinear behavior. In the multi–panel PMC infill system, primary damping arises from cyclic straining of the damping materials at the interface between the FRP laminates. As such, of concern herein is the availability of increasing the damping that arises from the cyclic straining of the materials in the composite frame, and the feasibility of the design concept. Frictional and nonstructural sources are not considered herein. Therefore, the exact overall damping of a structure is not quantified. The experimental results are evaluated by considering force–displacement curves, the stiffness degradation under successively applied cycles, and the dissipated energy. The experimental hysteretic responses are shown in Figure 7. Figure 7a presents the hysteretic responses before or after the PMC sandwich infill contacted the steel frame. It is observed that the outer FRP damping panels produced the damping without significant lateral resistance, while the increased lateral resistance of the structure was provided by the PMC infill beyond the point where the contact took place. The hysteretic energy observed during the applied cycles of the tests is compared for the steel frame and the multi–panel PMC infilled frame. By comparing the hysteretic energy of both cases in Figure 7b, one can observe the effect of the application of the combined interface damping layers at 0.16% drift It is evident that the enhanced energy dissipation produced by the interface damping layers will be effective in attenuating the seismic response of the structure and will be competitive with other similar seismic strategies, such as concrete shear walls and masonry infill walls, which currently dominate the market for mid–rise structures.

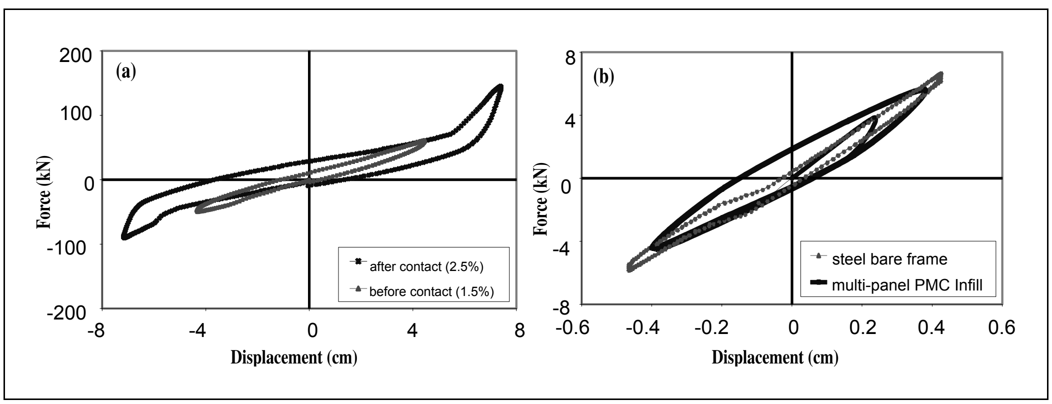


Figure 7. Hysteretic behavior of the multi–panel PMC infilled frame tests

Concluding Remarks

The multi-panel PMC infill system was designed to provide considerable stiffness as well as enhanced damping properties. According to the numerical and experimental studies, using the passive concept of combined interface damping layers provided enhanced damping characteristics through the outer damping panels. Also, as lateral drift increases, the contribution of the PMC sandwich infill panel can increase the stiffness when it wedges within the steel frame; thus, the additional contact and enhanced stiffness provide a mechanism to avoid excessively large relative floor displacements. Moreover, the influence of this stiffening by the PMC sandwich infill panel minimizes damage to the steel column.

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