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ANALYSIS AND EXPERIMENTAL STUDIES OF POLYMER MATRIX COMPOSITE (PMC) INFILL PANELS

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SUMMARY

In this paper, conceptual design, fabrication, and testing of advanced polymer matrix composite (PMC) infill panel system within a steel frame are presented. Such a system is designed to have multi–panel PMC infill with passive energy mechanism that is intended for seismic retrofitting. The basic configuration of this system is composed of two separate components—namely, an inner PMC sandwich panel and outer damping panels. The interaction of these two components produce the desired stiffness and enhanced damping properties in the structure following different drift level. As part of this research, analytical and experimental studies were performed to investigate the effectiveness of the proposed multi–panel infill concept. The pre-fabricated multi–panel PMC infill holds a great promise for enhanced damping performance, simplification of the construction process, and the reduction of time and cost when used in seismic retrofitting applications.

INTRODUCTION

In the U.S., many older existing structures that are 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 United States are structural frames infilled with unreinforced clay brick, concrete masonry, or structural clay tile. This infill construction has been prevalent since the late 1800s and still quite popular in the moderate seismic regions of the central and eastern United States. However, there are conditions in cast–in–place construction where cost, time constraints, or limiting disruptions to building operations may dictate other solutions. A new rehabilitation scheme is needed that will simplify the construction process; reduce time, cost and inconvenience of construction; and reduce the obstruction to functional use of structure both during and after construction. Some disadvantages associated with many of the traditional strengthening techniques have led researchers to the development of innovative methods based on the use of 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 due to their superior strength–to–weight ratio, stiffness–to–weight ratio, and durability in corrosive environments as compared

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with conventional materials. Such benefits carry the potential to conveniently and effectively aid in the mitigation of earthquake damage. From the 1980s, the U.S. 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 for various levels of seismicity, and to develop advanced strategies for repair and retrofitting. Nonstructural rehabilitation was accomplished through replacement, strengthening, repair, bracing, or attachment. The NSF research efforts had been supplemented by many researches carried out at the National Center for Earthquake Engineering Research (NCEER). Recently, due to additional research needs, new rehabilitation approaches for critical facilities have been identified. Hospitals are classified as one element of the most important public facilities and important part in the 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 the research initiatives of the Multidisciplinary Center for Earthquake Engineering Research (MCEER) in the area of advanced analyses and protective technologies for seismic retrofitting of critical facilities, FRP composite materials have been investigated as a new seismic strategy. The proposed methods may provide the solution for dealing with cost-effective retrofitting strategies for maintaining functionality of critical facilities and their contents during earthquakes. As an innovative alternative, the lightweight fiber reinforced polymer (FRP) composites have potential to emerge as an alternative material for non-structural elements such as infill walls that can be used as seismic retrofitting strategy in regions of moderate to high seismicity.

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 described. Moreover, the testing phase of the PMC infill within a steel frame to investigate the effectiveness of the system as one approach of seismic retrofitting is presented. The scope of this research was focused on the shear deformation of both combined interface damping layers and the structural response of a steel frame infilled by the multi–panel PMC infill wall submitted to monotonic and cyclic loads.

POLYMER MATRIX COMPOSITE (PMC)

Composite materials are made up of fibers bonded together with a resin matrix. The fibers are the primary load-carrying elements and provide the composites with their unique structural properties. When they are embedded in a resin matrix material, the matrix serves to bind the fibers together, transfer loads to the fibers, and protect them against environmental factors and damage due to handling. Depending on the type of application, the fibers can be oriented in a multitude of directions to enhance the mechanical properties of the composite in the desired direction.

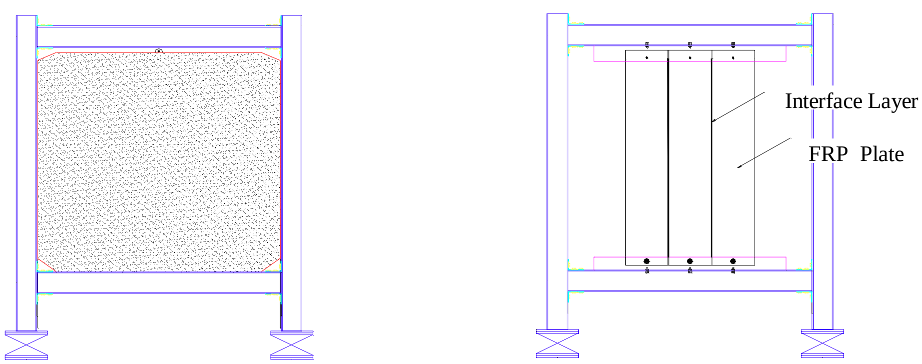
In this study, E-glass in the form of a woven fabric was chosen to manufacture the infill panels. The selected woven roving is composed of direct rovings woven into a fabric. The input rovings are designed to give a rapid wet-out and excellent laminate property. It is commonly denoted as "Style 7781" in the industry and has similar number of yarns, approximately 2.17 and 2.27 yarns per unit length (cm) in the fill and wrap directions. For a resin matrix, a matrix of vinyl ester resin (DERAKANE 411), which is a matrix produced by the Dow Corporation, was chosen to fabricate the PMC wall system. The DERAKANE vinyl ester resin is a premium-quality thermosetting product that can be used to fabricate a wide range of corrosion-resistant FRP applications. Finally, a multi-layer E-glass woven roving in a matrix of vinylester resin, Derakane 411, was designed as a form of FRP composite system and tested according to the American Society for Testing and Materials (ASTM) specifications. These coupons were fabricated to have the same number of fibers along wrap and fill directions for easy construction. In this study, material properties were obtained from a previous research by Kitane [7] because the same FRP laminates were employed for the design and fabrication process of the infill panels. Accordingly, material properties are modeled as a homogeneous, linear elastic, and orthotropic material. Table 1 presents the obtained FRP laminate material properties.

Table 1. Summary of FRP Material Test Results used in the Multi-panel Infill Panel System (Yasuo Kitane [7], unit = MPa)

	Longitudinal Direction			**Transverse Direction**		
Method	Tension	Compression	Shear	Tension	Compression	Shear
Width (cm)	1.26	0.65	2.54	1.26	0.65	2.77
Thickness (cm)	0.14	0.5	0.16	0.135	0.5	0.156
Elastic Modulus	16640	15868		17914	22489	
Shear Modulus			2718			2450
Poisson's ratio	0.129	0.1		0.13	0.25	
Ultimate Stress	284.6	241.2	56.0	335.5	261.8	63.8

CONCEPTUAL DESIGN AND CONSTRUCTION

The basic design philosophy and structural technique considered herein focus on increasing the efficiency for retrofitting a structure before and after earthquake damages. 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 structural configurations. From a construction point of view, PMC infill systems can be easily installed during the strengthening and retrofitting process of existing structures. The proposed multi–panel PMC infill system is composed of two separate basic structural components and they are: 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 system emphasizes 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 causes 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.



1) Inner PMC Sandwich Infill 2) Outer FRP Damping Panel

Figure 1. Configuration of A Multi-panel PMC Infill System

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 (Aref and Jung [2]), the dominant failure mode 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, but also by 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, Fig. 2 shows the maximum buckling force that was obtained from finite element analysis (ABAQUS [1]).

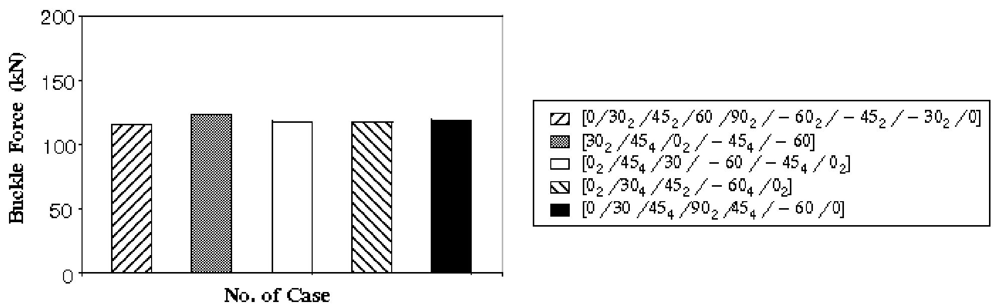


Figure 2. Results for Maximum Buckling Force of Applied Fiber Stacking Sequences

For the steel frame with infills, the presence of any gaps between the columns and the infill wall and/or between the top beam and the infill wall may be unavoidable. According to Riddington [6], these gaps may negate some or all of the stiffness provided by the infill. In the design of the PMC sandwich infill, these unavoidable gaps between the infill and the opening of steel frame can be used as an additional design parameter that affects the lateral resistance at specific drift. The 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 infilled frame structures because they are normally subjected to alternating loads. On the basis of the previous results (Dawe and Seah [3]), we assumed arbitrarily that the maximum side gap to be less than 0.4% of the infill dimensions even if there should be little decrease in the stiffness and/or strength of the infill action. By using finite element simulations representing the PMC infilled steel frame with different side gap distance at the boundary between the infill and the steel columns, the force–displacement response was evaluated. Finally, the designed contact target was chosen in the range between 2% and 2.5% lateral drifts that will allow enough shear straining of the combined interface layers.

For the outer damping panel design, the passive damping panel concept proposed by Gasparini et al. [5] was adopted, and basic consideration was given to have shear deformation of the interface layers between FRP plates along the relative motion of the top and bottom beams. These outer FRP panels should be designed so as to achieve initial static stiffness and an acceptable maximum strain at the interface layers. The selected FRP laminate was the same materials that were used in the fabrication of the inner PMC sandwich infill, and the proposed interface damping layers consisted of two composite damping materials —namely, 3M viscoelastic solid and polymeric honeycomb materials. The basic concept of these combined composite damping materials was proposed by Jung and Aref [4] and the enhanced damping property was observed by experimental and analytical studies. Practically, the proposed damping system could be utilized in as many panels as necessary to achieve different levels of damping and stiffness. In this study, the geometric configuration of the outer damping panels was determined to have three FRP laminate plates and two combined interfaces that contain damping materials (solid viscoelastic material and polymeric honeycomb) as shown in Fig. 3.

As a key design parameter of the combined interface damping layers, the design can be carried out based on the desired 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 [2]. As shown in Fig. 3(a), an idealized symmetric motion was assumed; accordingly, the thickness of FRP laminates was designed to have rigid body motion that produced 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. The selected mixing ratio of viscoelastic material was designed to have about 60% of total damper area, while the polymeric honeycomb material was used in the remaining portion of the combined damping layer. The purpose of having the honeycomb portion at the interface is primarily to: (1) provide the stiffness, (2) contribute to the damping output, and (3) prevent the crushing of the viscoelastic material.

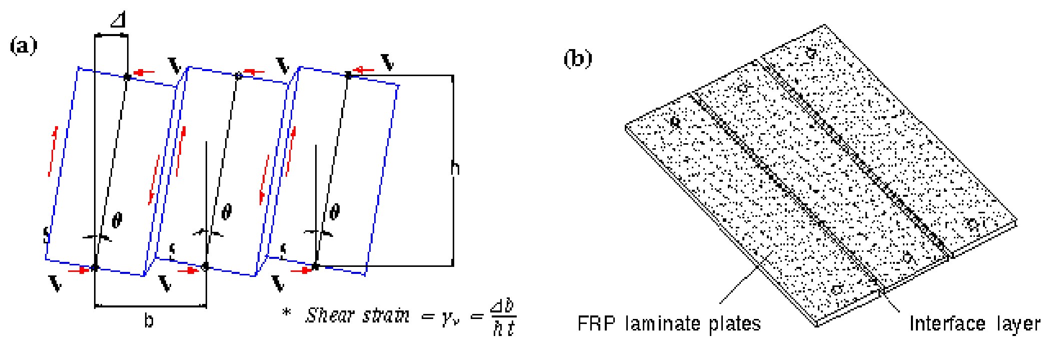


Figure 3. Design and Construction of the Outer Damping Panels: (a) Geometry of the Deformed Panels during Inter-story Drift (Gasparini et al., 1981; (b) Fabrication

EXPERIMENTAL INVESTIGATION AND RESULTS

In the experimental phase, testing of steel frame with and without composite infill wall was planned. Considering the experimental setup procedure, a steel frame with the PMC sandwich infill was tested first. Fig. 4(a) 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 allowing top and side gaps between the infill and the opening perimeter of the steel frame. Consequently, the outer damping panels were setup as shown in Fig. 4(b) and tested to evaluate the overall response of the multi–panel PMC infilled frame structure. Monotonic and cyclic loading were applied in the tests.

(a) Steel Frame Infilled with the PMC Sandwich Infill

(b) Steel Frame Infilled with the 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. Fig. 5(a) presents the numerical and experimental responses of the PMC sandwich infill panel with allowing initial gaps under push–over load. The force–displacement relation obtained from the test clearly indicated that the contact point of the PMC infill (with 7.6 mm initial side gap) took place at a lateral displacement of approximately 5.0 cm. Beyond that point, there is a progressive increase in lateral load resistance as the contact area increases and the PMC sandwich infill wedges at the corners of the steel frame. From the stress and strain outputs of the testing of the steel frame infilled with PMC sandwich panel, the compressive strut angle for the PMC sandwich infill was evaluated and compared with the numerical results as depicted in Fig. 5(b).

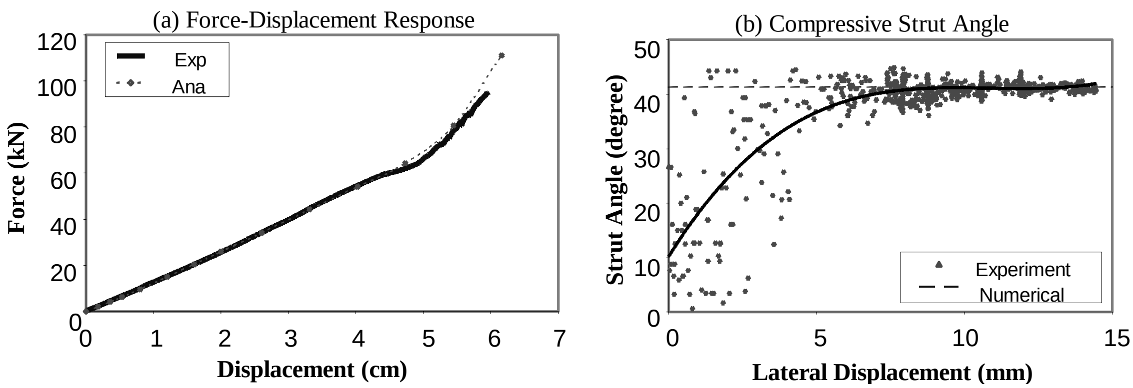


Figure 5. The Results of the Steel Frame Infilled with the PMC Sandwich Infill (1.0% Drift, Push-over Load Test)

Testing of a Steel Frame with the Multi–panel PMC Infill

Monotonic tests were conducted at 0.5%, 1.0%, and 1.5% lateral drift. Important information about in–plane stiffness and the effect of the interface layer can be obtained from such experiments. As shown in Fig. 6(a), 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 and the polymeric honeycomb. 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 inch larger than the bolt shaft diameter. As such, there was a slippage between the bolt shank–to–bolt holes until locking the pin or slot connector in place. Once a desirable locking configuration was achieved, the interface layer experienced shear strain. Fig. 6(b) presents the shear deformation of the interface layer after locking of the connectors.

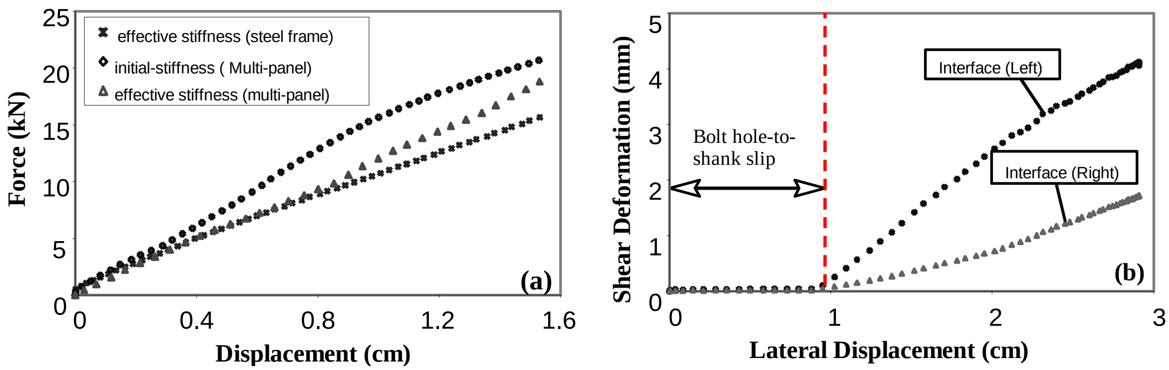


Figure 6. The Results of the Steel Frame Infilled with the Multi-panel PMC Infill (1.0% Drift, Push-over Load Test)

Finally, attention was given to the experimental investigation of the energy dissipation that existed in the multi–panel PMC infilled frame. Generally, the overall damping exhibited by a structure may arise from many sources, such as cyclic straining of structural and nonstructural elements, friction at interfaces, and nonlinear behavior. In the case of the multi–panel PMC infill system, the primary damping arises from cyclic straining of the damping materials at the interface between the FRP laminates. As such, of concern is the damping that arises from the cyclic straining of the materials in the composite frame. Therefore, frictional and nonstructural sources are not considered herein, and the exact overall damping of a structure is not quantified. The experimental results were evaluated by considering force–displacement curves, the stiffness degradation under successively applied cycles, and the dissipated energy. The experimental hysteretic responses are shown in Fig. 8(a) and (b). Fig. 8(a) presents the hysteretic responses before or after the PMC sandwich infill contacted the steel frame. It was 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 Fig. 8(b), one can observe that the effect of the application of the combined interface damping layers at 0.16% drift. Moreover, it was evident that the enhanced energy dissipation produced by the interface damping layers can effectively attenuate seismic response of the structure.

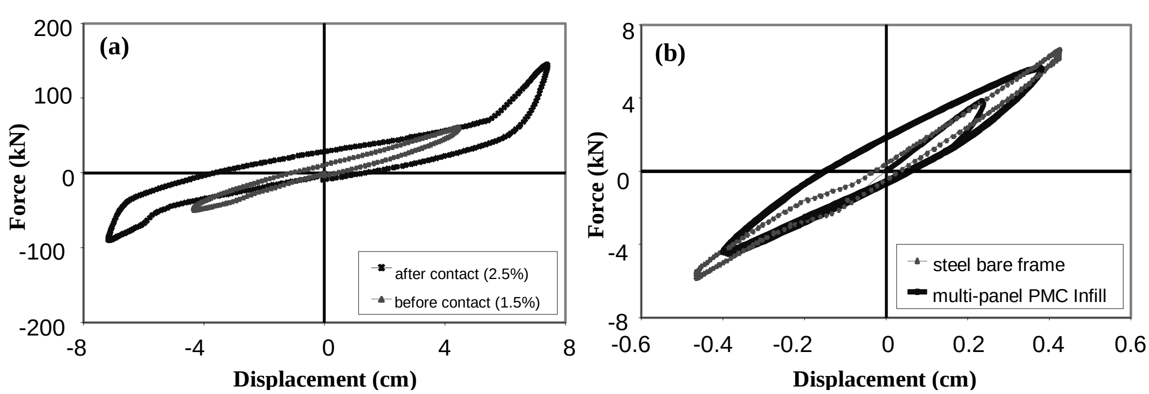


Figure 7. Hysteretic Behavior of the Multi-panel PMC Infilled Frame Tests

CONCLUSIONS

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, the combined interface damping layers provided enhanced damping characteristics through the shear deformation of outer damping panels at these interfaces. 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 excessive relative floor displacements. However, the influence of this stiffening by the PMC sandwich infill panel may create some damage to the beam-to-column connections.

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