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Seismic Excitation of Steel Frame Retrofitted by a Multi-Panel PMC Infill Wall

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***Abstract*—**A multi-panel PMC infilled system, using polymer matrix composite (PMC) material, was introduced as new conceptual design for seismic retrofitting. A proposed multi panel PMC infilled system was composed of two basic structural components: inner PMC sandwich infills and outer FRP damping panels. The PMC material had high stiffness-to-weight and strength-to-weight ratios. Therefore, the addition of PMC infill panels into existing structures would not significantly alter the weight of the structure, while providing substantial structural enhancement.

In this study, an equivalent linearized dynamic analysis for a proposed multi-panel PMC infilled frame was performed, in order to assess their effectiveness and their responses under the simulated earthquake loading. Upon comparing undamped (without PMC panel) and damped (with PMC panel) structures, numerical results showed that structural damping with passive interface damping layer could significantly enhance the seismic response.

***Keywords*—**Polymer Matrix Composite (PMC), Panel, Piece-wise linear, Earthquake, FRP.

I. Introduction

THE dynamic behavior of a large class of structural or mechanical systems can be adequately predicted by discrete models with finite degrees of freedom. The mathematical equations describing the dynamic responses on such models consist of ordinary differential equations. If the governing equations are linear, the system should be a discrete linear system. Discrete physical models of structural/mechanical systems are usually constructed with an assemblage of idealized masses, springs, and dashpots. For linear models, each of these elements is assumed to exhibit linear force-displacement behavior. The linear single-degree-of-freedom system is the most important discrete model because (1) a large class of structural/mechanical systems can be adequately modeled, and (2) the multiple-degree-of-freedom and continuous models of systems can be reduced to a set of single-degree-of-freedom systems under fairly general conditions using the normal mode approach.

In this study, the Polymer Matrix Composite (PMC) infill was introduced to enhance the seismic performance of building frames and its structural dynamic challenge was also simplified to formulate a single-degree-of-freedom (SDOF) system. The system was well-represented as an idealization of an one-story structure with a steel frame with PMC and without PMC panel. It consisted of a mass, m, concentrated at the roof level, a massless frame that provides stiffness to the system, and a viscous damper that dissipate energy of the system. A recent development in earthquake engineering has recognized the performance-based concepts for the seismic design of structures [1]. The seismic design of a structure is based on a specified target displacement for a given seismic hazard level. For this purpose, the structure was modeled as a single-degree-of-freedom (SDOF) system with equivalent elastic lateral stiffness and viscous damping properties representative of the global behavior of the actual structure at the target displacement.

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II. Experimental Test

Recently, a multi-panel PMC infilled system was proposed and studied by Aref and Jung [2]. The basic design philosophy and structural technique considered herein focus on increasing the efficiency for retrofitting a structure before and after earthquake damages. Fig. 1 showed the test specimen setup of PMC infilled wall. This test specimen consisted of a steel frame with the multi-layer PMC infill wall. A36 semi-rigidly connected steel frame members, which were designed for gravity loads and constructed according to the specifications of the American Institute of Steel Construction (AISC), were used to represent common design and construction practices of old building structures. The cross-sectional dimensions (U.S.) of beam and column members were W8x21 and W8x24, respectively. Gravity loading, which would be applied through the top beam, was not applied here. After manufacturing, the multi-layer PMC infill wall (85.6 by 92.0 inch) was placed within the steel frame opening (86.0 by 92.5 inch) to be tested.

Various measurement instruments were attached to the specimen to capture key data and to characterize the structural response of the multi-layer PMC infill wall. These key data included four major measurements obtained through the instruments attached: first, longitudinal and transverse strain measurements obtained from gauges placed at critical points on the PMC infill wall panel; second, the shear deformation of the polymer honeycomb material obtained through linear potentiometers; third, the hysteresis behavior and the corresponding strength and stiffness degradation measured using displacement transducers; and fourth, buckling of the PMC inner panel. Four sets of gauges were attached to the edge of each component in the PMC infill wall panel, and three linear variable differential transformers (LVDTs) were also placed on the column next to the test specimen using magnetic bases so that the LVDT tips touched the left column flange of the test specimen. Out-of-plane LVDT measurement was inconsistent and depended on the exact location of the buckling mode, and the data obtained from pairs of strain gauges located on the surface of the laminates were only marginally useful in tracing the stress contour because of the impact and vibration during testing. Fig. 2 illustrated various measuring instruments attached to the multi-layer PMC infill frame tests.

Full-scale specimens described in this study were tested with both monotonic and cyclic loading. Loading history was considered based on the previous infill wall test by Mander et al. [3], at the Structural Engineering and Earthquake Simulation Laboratory at the University at Buffalo. All cyclic tests for the multi-layer PMC-infilled frame were performed under displacement control, and were nearly identical. The suggested loading history in this study consisted of a series of stepwise increasing deformation cycles (multiple step). For each step, the test specimens were cycled two times at the assigned lateral displacements, and the displacement level was increased gradually according to the observed behavior. A sinusoidal wave form was then used to control the input displacement histories.

Fig. 3 showed the hysteretic response of the PMC-infilled frame under the successive loading drifts. Clearly, the behavior of the PMC infill wall was ductile, and the frame withstood large deformation without any significant strength or stiffness degradation before the buckling of the inner panel took place at 2.5% lateral drift.

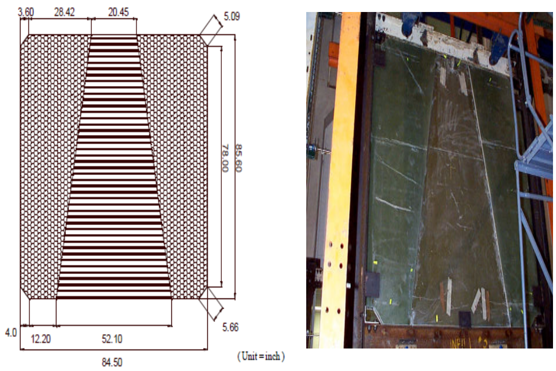

Fig. 1 PMC infilled wall test setup

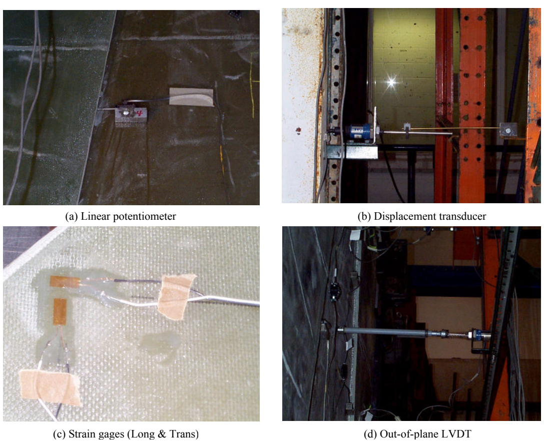

Fig. 2 Typical instruments for the experimental test

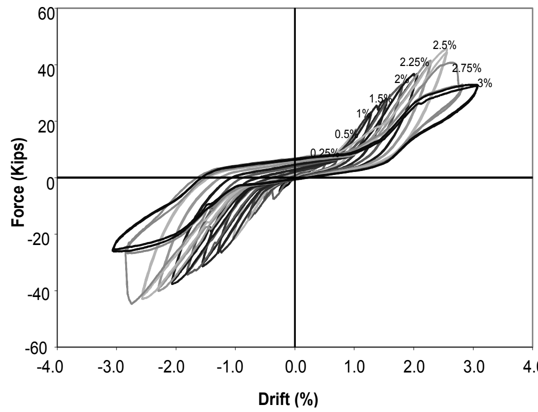

Fig. 3 Hysteretic response of the PMC infilled wall

III. Linear Elastic Dynamic Modeling

A. Simplified Linear Elastic Dynamic Modeling

For the numerical simulation of the tests, however, the dense meshing using special contact elements or other nonlinear elements, which cause computationally ineffective, was often required in Finite Element (FE) analysis. Therefore, the equivalent linearization method was proposed in the next section to reduce computational effort.

The idealization of the multi-panel PMC infill system as an equivalent SDOF system subjected to seismic loading was illustrated in Fig. 4. The hysteretic behaviors obtained from harmonic cyclic loading tests were used to first determine the parameter to obtain the SDOF response prediction for PMC infill systems. The dynamic analysis for equivalent linear SDOF systems may produce approximate solutions with an assumption that frame members as well as FRP composite components would remain linear up to the infill's elastic buckling failure. The equation of motions for this SDOF system can be expressed.

$$m\ddot{u}(t) + c\dot{u}(t) + ku(t) = -m\ddot{u}_g(t) \tag{1}$$

Dividing by m gives

$$\ddot{u}(t) + 2\xi_{eq}\omega_n\dot{u}(t) + \omega_n^2 u(t) = -\ddot{u}_g(t) \tag{2}$$

where, m=total mass including the PMC infill, ξ_{eq} = equivalent viscous damping ratio, k= stiffness, and $\ddot{u}_g$ = ground acceleration.

Also, the total equivalent damping ratio of the substitute structure, equipped with the visco-elastic energy dissipation device was:

$$\xi_{eq} = \xi_{steel} + \xi_{ED} \tag{3}$$

ξ_{steel} of 2% is the inherent steel damping ratio for steel building and 5% for reinforced concrete, RC building [4]. In addition, in order to incorporate various energy dissipation systems, the effects of the energy dissipation devices were represented by the effective viscous damping ratio. The effective viscous damping ratio provided by the viscoelastic device could be derived as follow [4],

$$\xi_{ED} = \frac{1}{4\pi}\frac{W_{viscoelastic}}{W_s} = \frac{1}{2}\frac{\sum_j \eta k_j u_o^2}{\sum_i F_i u_i} \tag{4}$$

where, $u_{o,i}$ is the relative displacement between the damping device j, F_i is the laterally distributed force at floor level i, k_i is effective stiffness. η is the loss factor of the viscoelastic material at the modal frequency of the original structure. Further information of the equivalent linearization of the multi-panel PMC infill system can be found in Jung Dissertation [5]. Finally, dynamic properties of the test structures with and without PMC infill systems were determined by (1) to (4). Fig. 5 showed the force-displacement relationship of the linear visco-elastic damper under periodic excitation.

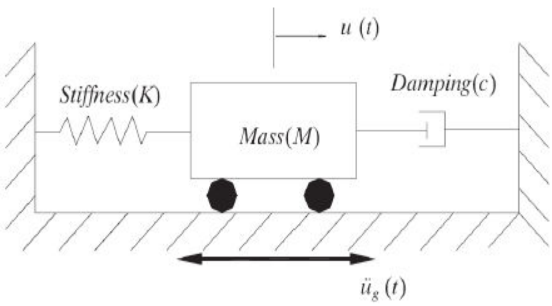

Fig. 4 Motion of equation of SDOF system

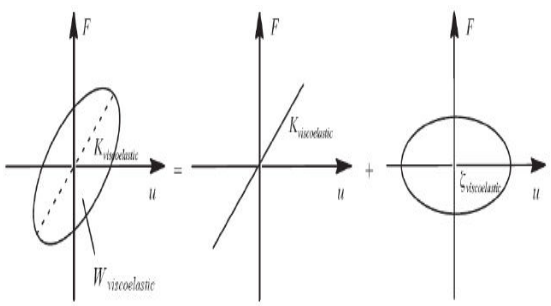

Fig. 5 Modeling of viscoelastic device

IV. Loading Protocol for the SDOF PMC System

A. Seismic Ground Motion

Dynamic linear time history analyses were performed. Unlike non-linear time history analysis, which represented the dynamic characteristics of the system in detail, a linear time history analysis was quite conservative and yet approximate. In this study, since it is not intended to develop design guideline for these systems and the objective is to the investigation of the dynamic response, only one earthquake record is employed. Based on this method, more precise structural modeling and several site-representative ground motions are needed to determine the demand values for design purposes. An earthquake record - the El Centro S00E - is used as ground motion input. The applied earthquake, as shown in Fig. 6, has a peak acceleration of 0.348g.

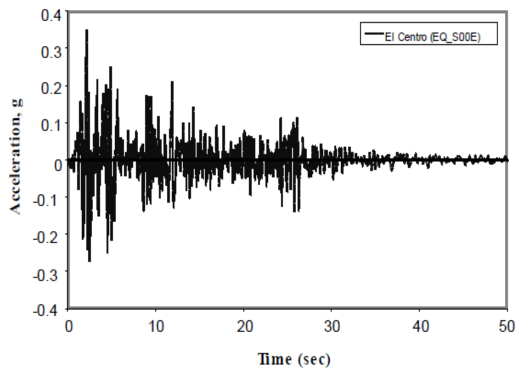

Fig. 6 Earthquake loading protocol: EL-Centro

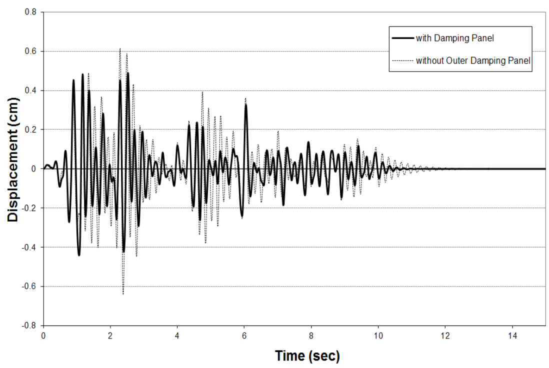

Fig. 7 The predicted dynamic responses of the PMC infill walls

V. Results and Conclusion

In this study, the equivalent linear dynamic analysis for a proposed multi-panel PMC infilled frame was performed, in order to assess their effectiveness and their responses under the simulated earthquake loading. Fig. 7 presented the predicted seismic displacement response of equivalent linearized SDOF system for PMC infill panel systems. By comparing the test result from undamped and damped structures, the structural damping with passive interface damping layer significantly enhanced the seismic response. As can be seen in the result, the response of the equivalent linearized damped model produced more conservative results in comparison to that of undamped PMC system.

Further, for the actual responses of the multi-panel PMC infill systems, the proposed equivalent linear model can be verified in this study due to the absence of dynamic experiments. Therefore, more research related to experimental tests and corresponding nonlinear dynamic model needs to be developed with more accurate design criteria, in order to predict realistic dynamic behavior.

Acknowledgment

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