Equivalent Linearization of Polymer Matrix Composite Infill Wall Subjected to Seismic Ground Motions

BuSeog Ju [1] and WooYoung Jung [*2]

[1] The Department of Civil Engineering, North Carolina State University, Raleigh, NC, USA
[*2] The Department of Civil Engineering, GangNeung-WonJu National University, GangNeung, South Korea
[*2] woojung@gwnu.ac.kr

Abstract—**Polymer Matrix Composite (PMC) material was introduced as a new conceptual infill construction for seismic retrofitting. A proposed PMC-infilled system was composed of two basic structural components: inner PMC-infilled sandwich and outer FRP damping panels designed to constrain the energy-dissipating layers. These two components along with the steel frame were intended for providing the desired stiffness and damping following different drift values. The observed behavior of the proposed PMC-infilled system was evaluated experimentally based on the stiffness, the mode of failure and the energy dissipation outputs. In this study, a piece-wise linear dynamic analysis for a proposed PMC-infilled frame was performed according to the previous research, for the assessment of their effectiveness and the responses under the simulated earthquake loading. Upon comparing the results of 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. Furthermore, the numerical simulation response showed that the response of the equivalent linearized model produces more conservative results, in comparison to the response of piece-wise linear model.**

Keyword-Polymer Matrix composite (PMC), Panel, Piece-wise Linear, Earthquake, FRP

I. INTRODUCTION

In recent years, polymer matrix composite (PMC) materials have received considerable attention for use in civil infrastructure applications ranging from the retrofit and/or rehabilitation of buildings and bridges to the construction of new structural systems. Due to their light weight, high stiffness to weight and strength to weight ratios and potentially high resistance to environmental degradation that led to lower life cycle costs, civil engineers were recognizing the high potential for advanced polymer composites as an alternative construction material. In addition, the fiber reinforced polymer (FRP) composites were playing an increasingly important role in civil engineering applications. Even greater promise exists for the advanced concept of joining composites with traditional materials in order to form hybrid structures. The reason(s) for the increasing prominence of these materials were due to its related to the ability of these materials to be tailored to suit for particular environments in different conditions compared with conventional materials.

Hence, many researchers [1-4] studied the behavior and associated analytical models of the infilled frames with different materials under the monotonic loading. The role of infill walls in strengthening and stiffening the structure as a whole, under cyclic and earthquake loading was also investigated by a number of researchers [5-10]. In addition, the equivalent structure approach to replace the nonlinear structure was suggested by many researchers [11-15].

This paper presented a framework for evaluating equivalent linearization of PMC infill wall subjected to earthquake ground motions. 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 were linear, the system should be a discrete linear system. Discrete physical models of structural/mechanical systems were usually constructed with an assemblage of idealized masses, springs, and dashpots. For the linear models, each of these elements was assumed to exhibit linear force displacement behavior. The linear single degree of freedom system was 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 set of single degree of freedom (SDOF) systems under fairly general conditions using the normal mode approach.

Furthermore, a recent important development in earthquake engineering has recognized the performance based concepts for the seismic design of structures [16]. The seismic design of a structure was 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. This paper was divided in four sections: 1) experimental tests of PMC infill wall; 2) simplified linear elastic dynamic modeling; 3) piecewise-linear dynamic modeling; 4) dynamic analysis of single degree of freedom (SDOF) system.

II. EXPERIMENTAL TEST SETUP

A. Polymer Matrix Composite (PMC) Panel

Composite materials were made up of fibers bonded together with a resin matrix. The fibers were the primary load-carrying elements and provide the composites with their unique structural properties. When they were 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. Recently, a multi-panel PMC infilled system was proposed and studied by Aref and Jung [17]. The basic design philosophy and structural technique considered herein focused 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. Fig. 1 showed 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.
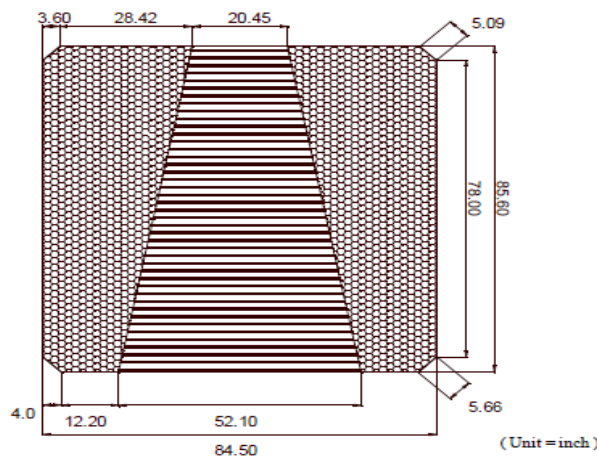

Fig. 1. Geometric Configuration of the PMC Infill Wall [1]

B. Polymer Matrix Composite (PMC) Infill Wall Test Setup

Fig. 2 showed the test specimen setup. 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. 3 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. [18], 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. 4 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. 2. Geometric Configuration of the PMC Infill Wall [1]

(a) Linear potentiometer

(b) Displacement transducer

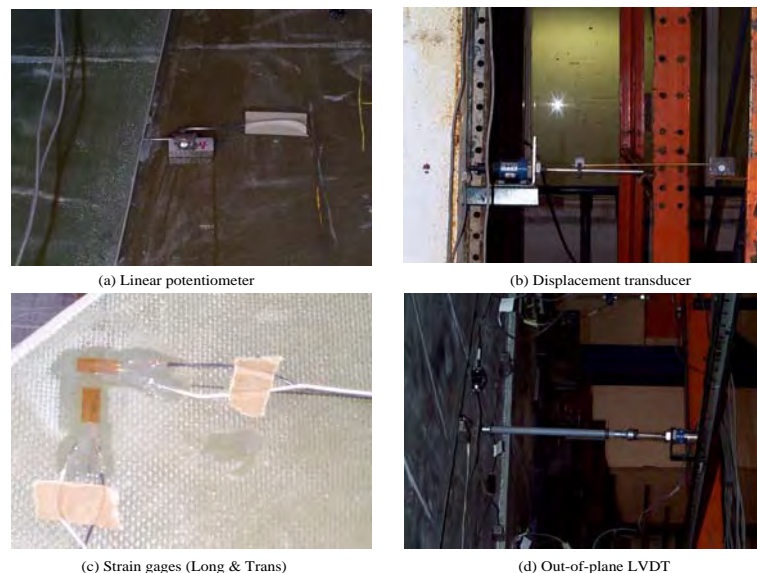(c) Strain gages (Long & Trans)

(d) Out-of-plane LVDT

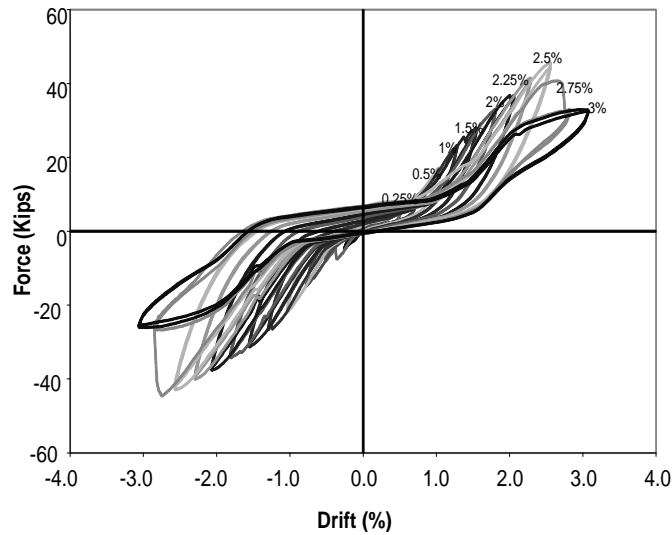Fig. 3. Typical Instruments for Experiments

Fig. 4. Hysteretic Response of the PMC Infilled Frame [1]

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 in order to reduce computational effort.

III. SIMPLIFIED LINEAR ELASTIC DYNAMIC MODELING

The idealization of PMC infill systems as an equivalent SDOF system, subjected to seismic loading, is illustrated in Fig. 5. The hysteretic behaviors obtained from harmonic cyclic loading tests were used to first determine the parameter to obtain the SDOF response prediction for the PMC infill systems. The system parameters were represented by the equivalent viscous damping and effective stiffness. The concept of equivalent viscous damping was restricted to systems vibrating at amplitudes within the linearly elastic limit of the overall structure. However, the advantage of using a linear equation of motion usually outweighs whatever compromises were necessary in the viscous damping approximation. Accordingly, 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 motion 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

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

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

In order to incorporate various energy dissipation systems, the effects of the energy dissipation devices were represented by the effective viscous damping ratio (ξ_{ED}) and the effective stiffness (k_{eff}) in this chapter. The viscous damping was defined as the energy dissipation mechanism where the damping force (F_D) was proportional to velocity. The linearized form is written as $F_D = c\dot{u}$, where c is the damping coefficient and $\dot{u}$ was the relative velocity. For nonlinear energy dissipation devices, it was convenient to obtain the effective viscous damping ratio by equating the energy dissipated per cycle of a periodic excitation to the corresponding value of linear viscous damping. This was given as [19],

$$\xi_{ED} = \frac{c}{c_{cr}} = \frac{c}{2m\omega_n} = \frac{W}{2\pi m\omega_n\omega u_0^2} = \frac{1}{4\pi}\frac{W}{\left(\frac{\omega}{\omega_n}\right)W_s} \tag{3}$$

where, c_{cr}, m, ω_n, W and W_s were the critical damping coefficient, mass, natural circular frequency, the enclosed area of the hysteresis loop, and the maximum stain energy of the system, respectively.

For structures subjected to earthquake loading, w/w$_n$=1.0 and, therefore, $\zeta_{ED} = \dfrac{1}{4\pi}\dfrac{W}{W_S}$ it would not be correct at any other exciting frequency, but it would be satisfactory approximation.

Fig. 6 showed the force-displacement relationship of the linear visco-elastic damper under periodic excitation. The enclosed elliptic area W=π c w u$_0^2$ was the energy dissipated by the added linear damping device that undergoes a cycle of periodic motion $(u(t) = u_0 \sin wt)$ of amplitude u$_O$ and frequency w.

To incorporate the frequency dependent damping ratio in time-history analysis, a simple model proposed by previous researches [20] was considered. The dynamic properties of viscoelastic materials such as shear storage, shear loss modulus, and loss factor were usually functions of frequency and temperature. The frequency at which the viscoelastic damper operates was approximately the same as the structural modal frequency. Numerically, the natural frequency and equivalent structural damping of a viscoelastically damped structure can be satisfactorily predicted using the modal strain energy method. Accordingly, the effective viscous damping ratio provided by the viscoelastic device can be derived as follow [21],

$$\xi_{ED} = \frac{1}{4\pi}\frac{W_{viscoelastic}}{W_s} = \frac{1}{2}\frac{\sum_j \eta k_j u_0{}^2{}_j}{\sum_i F_i u_i} \tag{4}$$

u$_{0,j}$ was the relative displacement between the damping device j, F_i was the laterally distributed force at floor level i , k$_i$ was effective stiffness. h was the loss factor of the viscoelastic material at the modal frequency of the original structure.

For a single-degree-of-freedom structure such as the PMC panels with passive damping mechanism shown in Fig. 7 and oscillating at frequency ω, the force corresponding to the addition of a viscoelastic interface layers with shear area (A$_v$) and thickness (t) took from

$$f = c(w)\dot{\delta} + k(w)\delta = \beta[c(w)\dot{\Delta} + k(w)\Delta]$$
$$c(w) = \frac{A_v G''(w)}{wt} \quad k(w) = \frac{A_V G'(w)}{t} \tag{5}$$

where $G'(\omega)\ and\ G''(\omega)$ were shear storage and loss modulus of the viscoelastic material, and β was the position factor considering the installation of viscoelastic materials.

From Fig. 7 [22], letting the shear deformation of interface layers, δ, inter-story displacement, D, thickness of the interface layer, t, and width (b) and height (h) of damping panel.

For the shear deformation and strain of the interface layer,

$$\delta = \left(\frac{b}{h}\right)\Delta, \quad \gamma_v = \frac{\Delta b}{ht} \tag{6}$$

Further, the static lateral stiffness of n interface layers may be expressed using energy method as follow;

For external energy work,

$$W_E = \frac{1}{2}K_{lat}\Delta^2 \tag{7}$$

For internal energy work,

$$W_I = \frac{n}{2}G_v \gamma_v{}^2 V \tag{8}$$

where G$_v$, g$_v$ presented shear modulus and strain of the interface layer and V was the volume of the interface layer (i.e. V = A$_v$ x t, where A$_v$ was the interface area and t was the thickness).

Upon substituting g$_v$ and V into equation (8), then the internal strain energy was

$$W_E = \frac{1}{2} K_{lat} \Delta^2 = \frac{n}{2} \left(\frac{G_v A_v}{t} \right) \left(\frac{b}{h} \right)^2 \Delta^2 \tag{9}$$

The energy equation, $W_E = W_I$, can now be solved for k_{lat}, that is, the strain energy in the interface layer should now equal to the work done by the applied load. Finally, the static lateral stiffness produced by the interface layers is

$$K_{lat} = n \left(\frac{G_v A_v}{t} \right) \left(\frac{b}{h} \right)^2 \tag{10}$$

By equating the lateral stiffness shown in both equation (5) and (9), the position factor (β) can be determined. It was shown in equation (11) that the position factor (β) was related to the geometric dimension of the damping panels.

$$f = \beta[c(w)\dot{\Delta} + k(w)\Delta]$$
$$where, \quad \beta = \left(\frac{b}{h} \right)^2 \tag{11}$$

Combining the primary frame with the visco-elastic energy dissipation device, the total equivalent stiffness (K_{eq}) and the total equivalent damping ratio (ξ_{eq}) of the substitute structure equipped with the visco-elastic energy dissipation device were

$$K_{eq} = K_{steel} + K_{ED} \tag{12}$$
$$\xi_{eq} = \xi_{steel} + \xi_{ED} \tag{13}$$

ζ_{steel} of 2% was the inherent steel damping ratio for steel building, and 5% for reinforced concrete, RC, building [21]. When properly designed, steel frames were very efficient in resisting forces generated from ground motion because of their ability to dissipate seismic energy through large inelastic deformation and damping. In recent years, tremendous interest has been generated in the study of the dynamic behavior of frames with non-rigid connections [23]. Connection flexibility tended to reduce frame stiffness and, thus, increased the vibration period of the frame.

For the structure with PMC infill systems, in order to capture the energy dissipation characteristics at a given displacement amplitude, D, an equivalent viscous damping ratio (ζ_{eq}) was computed from the global hysteretic behavior of steel frame and the expecting shear straining of the interface viscoelastic layer in each PMC infill panel system. For the purpose of practical application, more detailed parameters for the effective stiffness and equivalent viscous damping can be defined in equation (14), (15), and Fig. 8 according to the first natural frequency mode of undamped structure.

$$K_{ED} = K_{infill} + K_{interfacelayer-honeycomb} \tag{14}$$
$$\xi_{ED} = \xi_{infill-hysteretic} + \xi_{interfacelayer-viscous} \tag{15}$$

Finally, dynamic properties of the test structures with and without PMC infill systems were determined. The equivalent viscous damping ratio for the interface viscoelastic damping layers was calculated using equation (4). The dynamic properties for viscoelastic materials were obtained from data provided by 3M Company, Japan. As shown in Fig. 9, the equivalent viscous damping ratio for each energy dissipation PMC infill panel was computed at specified natural frequency of undamped structure. Natural circular frequency of the structure was 15.7 Hz for undamped steel frame. Table I summarized the mass, effective damping, and effective stiffness for equivalent SDOF system.

TABLE I
Summary of Dynamic Properties of Equivalent Linear SDOF systems for Energy Dissipating PMC Infill Panels

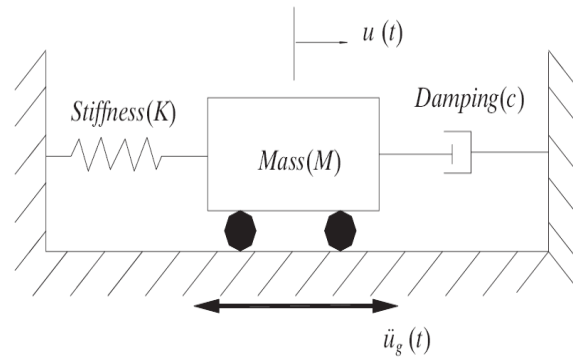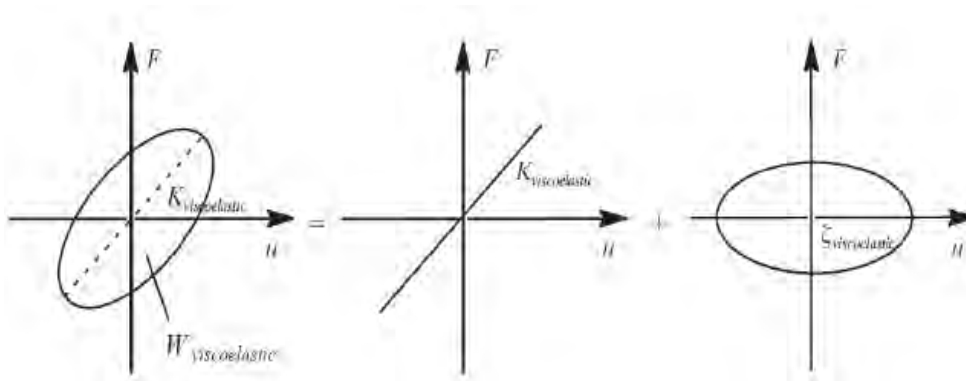|	Mass(kips – sec²/inch)	Eq_damping(ζ_{eq})	K_{eff}(kips/in)
Steel Frame	0.01036	0.02	6.4
Multi-layer Infill	0.0207	0.043	13.0
Multi-panel Infill	0.0116	0.055	12.2

Fig. 5. Motion of Equation for SDOF System
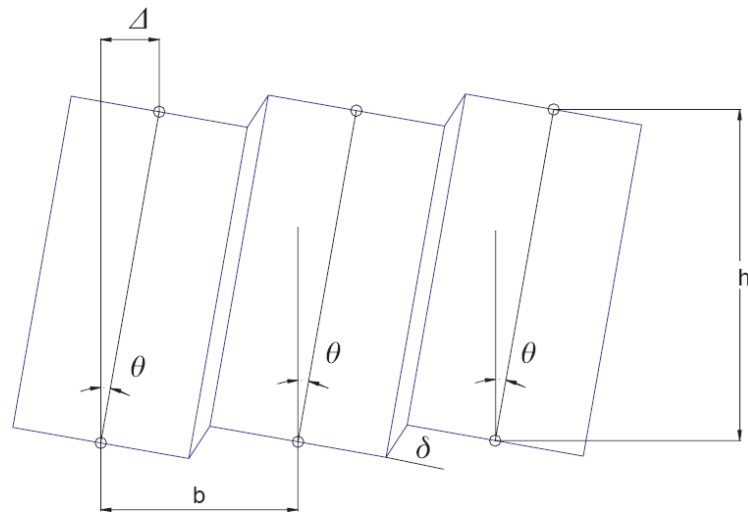

Fig. 6. Modeling of Viscoelastic Device

Fig. 7. Idealized Deformed Geometry of the FRP Damping Panel during Inter-story Drift [22]
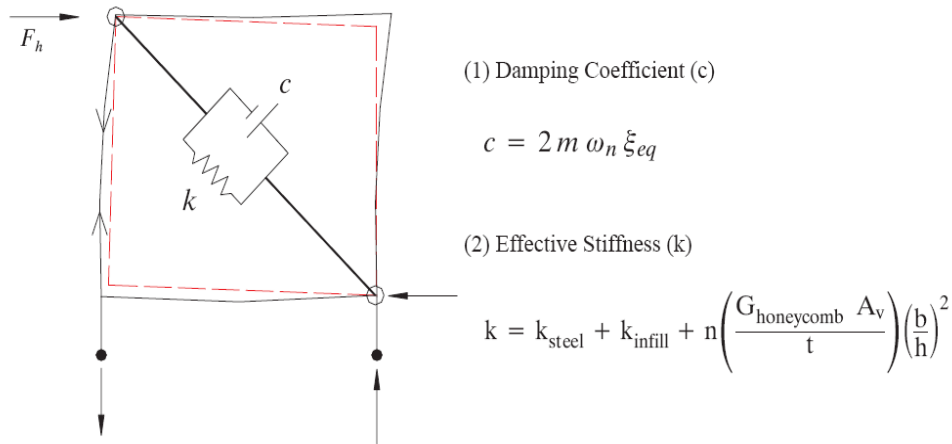
(1) Damping Coefficient (c)

$$c = 2\,m\,\omega_n\,\xi_{eq}$$

(2) Effective Stiffness (k)

$$k = k_{steel} + k_{infill} + n\left(\frac{G_{honeycomb}\ A_v}{t}\right)\left(\frac{b}{h}\right)^2$$

Fig. 8. Dynamic Parameters of the Simplified PMC Infilled Frame Analysis
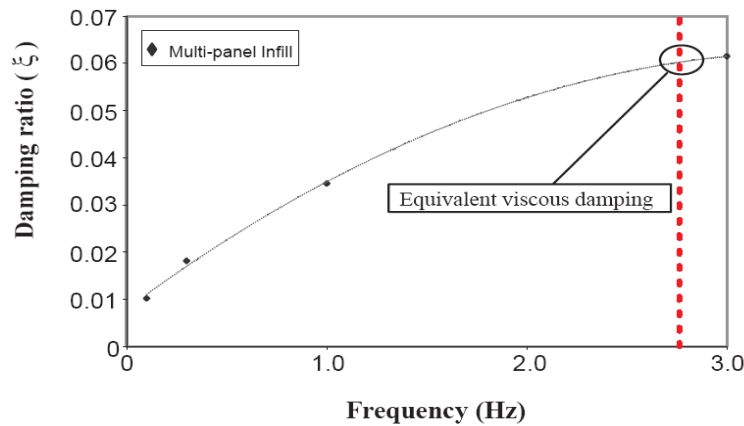
Fig. 9. Equivalent Viscous Damping Ratio of the Outer Panels in the Multi-Panel PMC Infilled Frame

IV. PIECEWISE LINEAR DYANMIC MODELING

For the purpose of more exact approach for the seismic response of the multi-panel PMC infilled frame structures, a piecewise-linear dynamic system was proposed in this study. Fig. 10 showed a schematic model of the proposed stiffening system (i.e. multi-panel infill system), with the base structure and its interaction with the PMC sandwich infill system.

A mass m was attached to a linear spring of both steel frame and viscoelastic interface stiffness, K_{steel}, β (K_{infill})and a linear dashpot with viscoelastic damping factor, c. A gap element with two operating states links the mass to an auxiliary linear spring of the infill stiffness, K_{infill}. Parameters defining the interacting PMC infill panel systems included stiffness, strength, and gap size. The gap size can be arbitrarily selected such that the interacting PMC infill engaged in the response of the base structure at different drift ratio.

By examining the experimental hysteretic behavior, the bi-linear force-displacement relation of frame-infill system was shown in Fig. 11. This simplification neglected energy dissipation in the wall and its boundaries due to any un-modeled inelastic mechanism which could significantly affect the wall's dynamic behaviors. Accordingly, overall energy dissipation mechanism can be modeled by an equivalent viscous damping.

When the system is externally excited, the equation of motion may be written as

$$m\ddot{u}(t) + c\dot{u}(t) + ku(t) + H(u,\dot{u}) = -m\ddot{u}_g(t) \qquad (16)$$

where $H(u,\dot{u})$ was the linear restoring spring resistance force term which increase the stiffness and strength after the gaps close.

In this model, the linear restoring force generated within the gap element is represented by

$$H(u, \dot{u}) = \text{sgn}(v) K_{\text{inf ill}}(u - u_o) = \text{sgn}(v) K_{\text{inf ill}} \Delta u$$

$$For, H(u, \dot{u}) = \begin{cases} \text{sgn}(v) K_{\text{inf ill}} \Delta u & if \ |u| \geq u_o \\ 0 & if \ |u| < u_o \end{cases} \tag{17}$$

where, K_{infill}, and contact displacement, u_O, were constant and sgn ($\bullet$) was the signum function defined as

$$\text{sgn}(v) = \begin{cases} 1 & if \ v > 0 \\ 0 & if \ v = 0 \\ -1 & if \ v < 0 \end{cases} \tag{18}$$

Newmark constant-average acceleration method was used to calculate velocity and acceleration in terms of displacement.
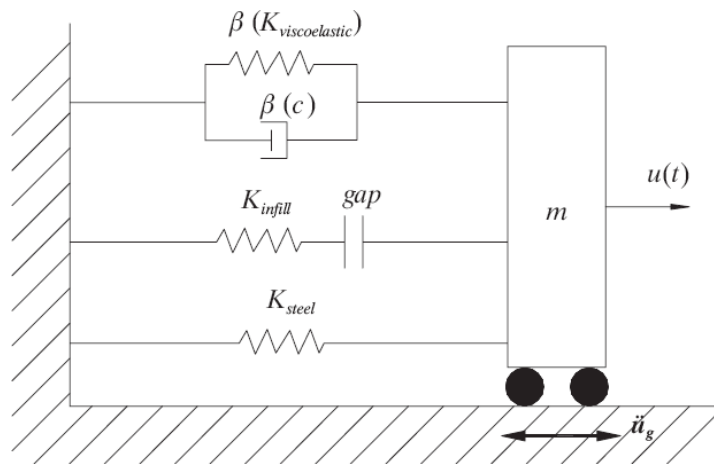
Fig. 10. Schematic Representation of a Stiffening System
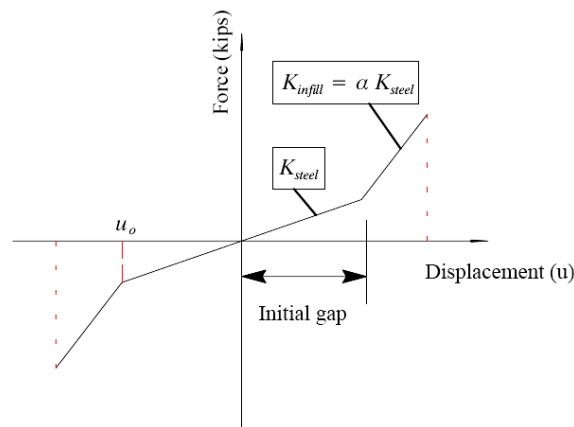
Fig. 11. Force-Displacement Relation of a Stiffening SDOF System

V. DYNAMIC ANALYSIS OF SDOF SYSTEM

A. Selected Ground Motion

Dynamic linear and a piecewise-linear time history analyses were performed. Unlike non-linear time history analysis which can represent the dynamic characteristics of the system in detail, linear time history analysis was quite conservative and yet approximate. In this study, since it was not intended to develop design guideline for

these systems and the objective was to investigate the dynamic response, only one earthquake record was employed. Based on this method, more precise structural modeling and several site-representative ground motions were needed to determine the demand values for design purposes. An earthquake record - the El Centro S00E - was used as ground motion input. The applied earthquake, as shown in Fig. 12, had a peak acceleration of 0.348g.

B. Newmark Method

A step-by-step numerical integration was used for determining the response of linear single-degree-of-freedom system. This approach was to approximate the derivatives appearing in the system equation of motion and to generate a step-by-step solution using time step D_{ti}. Although many such procedures were available for carrying out this numerical integration, one of most useful was the average acceleration method. In this study, the solution of equation (2) and (16) was achieved using the Newmark constant average-acceleration time integration scheme.
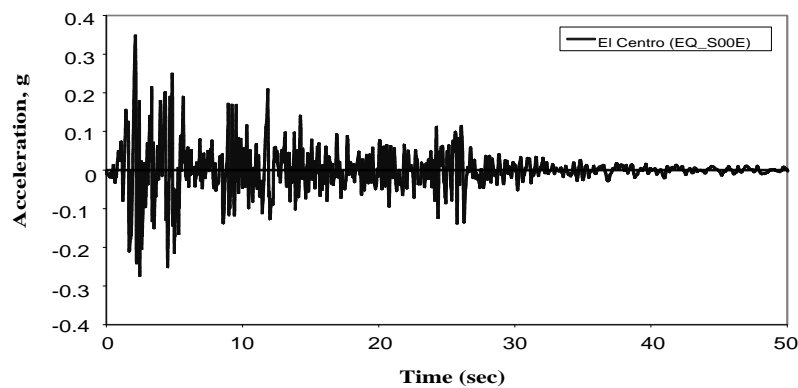
Fig. 12. Earthquake Ground Motion: El Centro (S00E)

VI. RESULTS AND DISCUSSION

In this study, a simple result from comparing undamped and damped structural seismic responses was drawn. Fig. 13 to 16 presented the predicted seismic displacement response of equivalent linearized SDOF systems for various PMC infill panel systems. By comparing tested undamped and damped structures, numerical results showed that structural damping with passive interface damping layer could significantly enhance the seismic response.

For the multi-panel PMC infill panel system, a piece-wise linear SDOF system was considered in addition to the linear SDOF system. The response of numerical simulation was shown in Fig. 17(a) and (b). It was observed that the response of the equivalent linearized model produces more conservative results when compared with that of piece-wise linear model. Fig. 17(c) illustrated the comparison of both results.

For investigating the effect of the contact behavior between the infill and the frame members, the prototype single-story frame was modeled by two equivalent single-degree-of-freedom systems. The first was the system without the contact effects (called here, case 1), whereas the second was with contact effects by the infill (case 2). Aside from the contact, all parameters for both cases were identical. In the numerical simulations, the following values were adopted as the system parameters: m = 0.0453 kips-sec^2 / in, ζ_{eq}= 0.075.

For the variation of the stiffness caused by the contact with the infill, the lateral stiffness was represented by two different values: 6.86 kips/in for before contact and 17.6 kips/in for after contact, respectively. The stiffness ratio before and after contact was 2.56. Without loss of generality, it was further assumed that $u(0) = \dot{u}(0) = 0$, namely, zero initial conditions were applied in this study. Maximum roof displacements observed during El-Centro 0.324g were 1.55 in for case 2 and 1.76 in for case 1. Fig. 18 and 19 presented the displacement response for both cases during El-Centro earthquake loading. It was evident here that the contribution of the PMC infill at high drift was helpful in reducing the inter-story drift in the structure. The numerical results for the comparison of both cases were illustrated in Fig. 20.
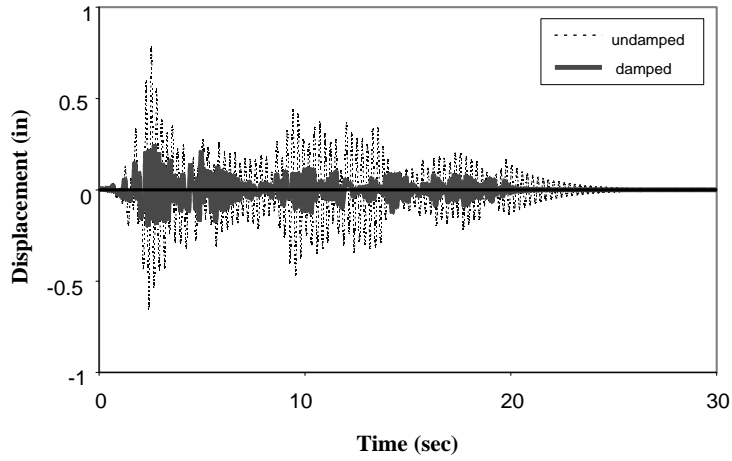
Fig. 13. The Predicted Dynamic Response of the Steel and Multi-layer PMC Infill Panel Systems
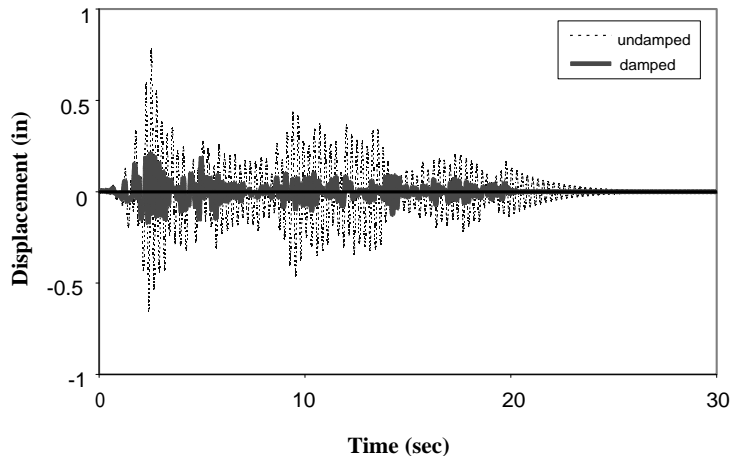

Fig. 14. The Predicted Dynamic Response of the Steel and Multi-panel PMC Infill Panel Systems
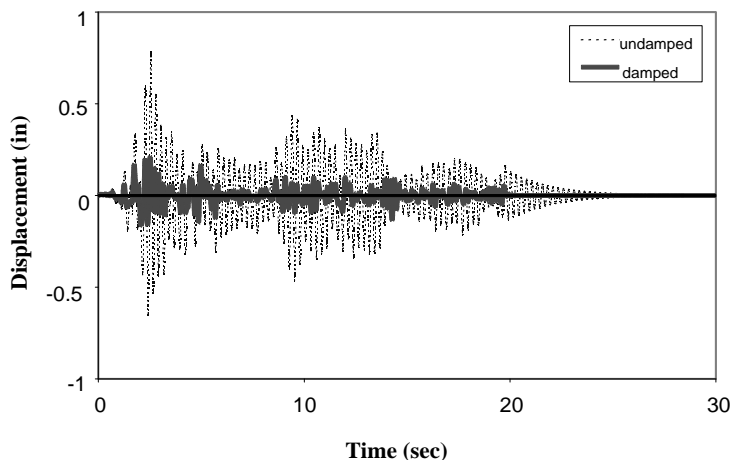

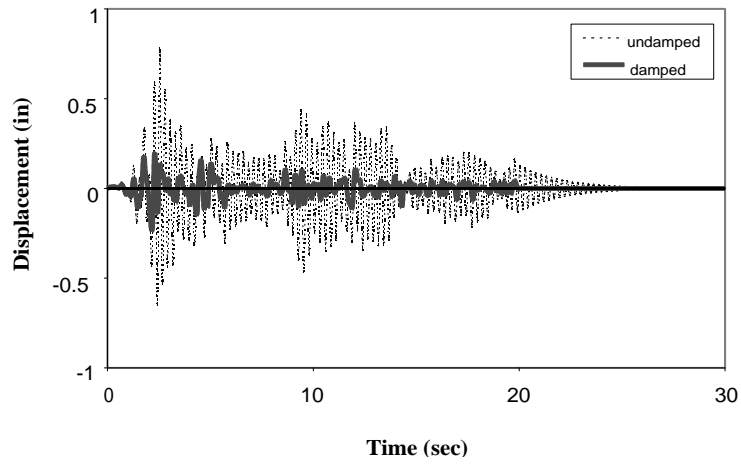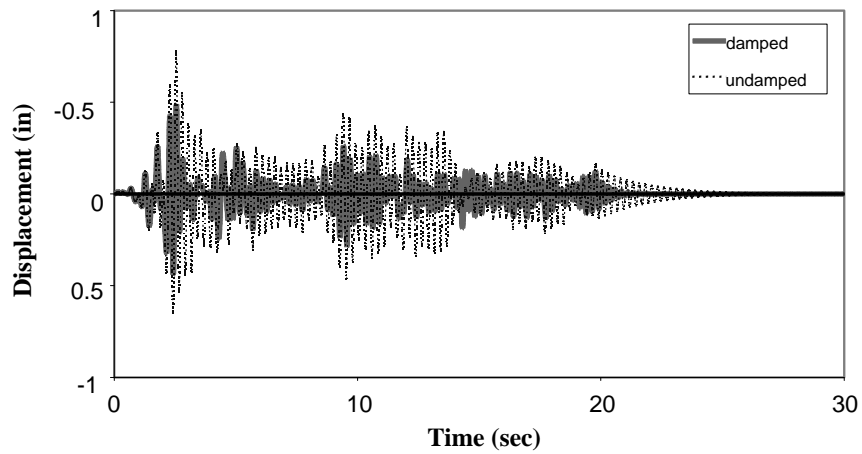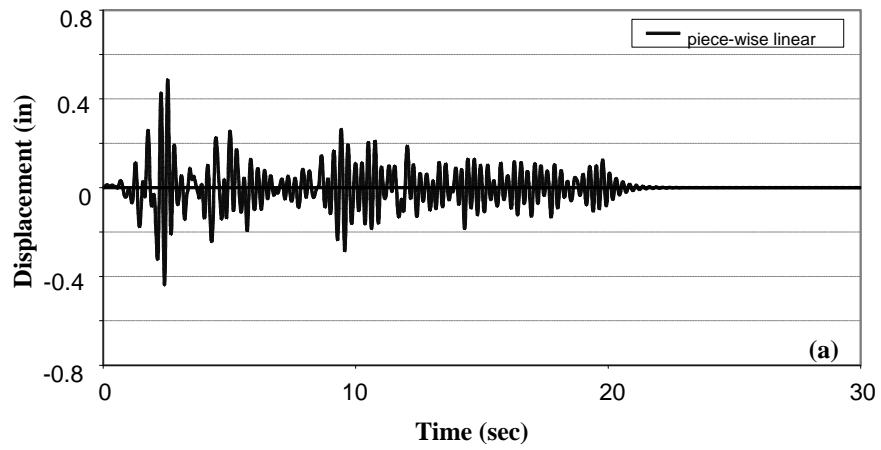Fig. 15. The Predicted Dynamic Response of the Steel Frame and FRP Box Infill Frame (Case 1)

Fig. 16. The Predicted Dynamic Response of the Steel Frame and FRP Box Infilled Frame (Case 2)
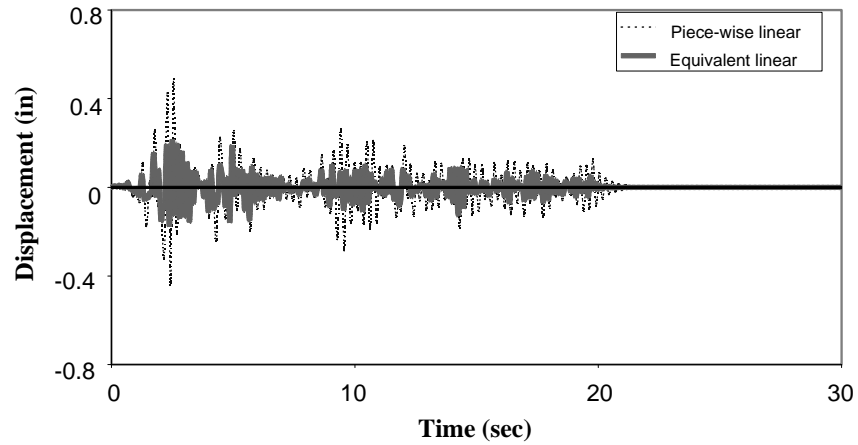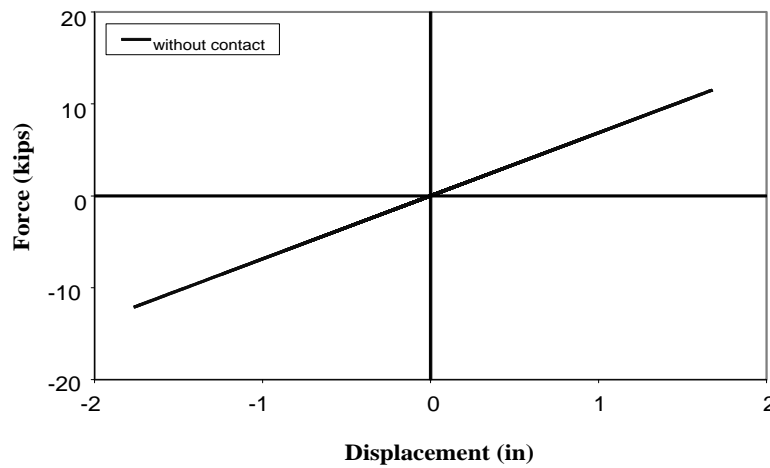
Fig. 17. The Predicted Dynamic Response of the Multi-panel PMC Infill System : (a) Response; (b) Comparison with Undamped Case; (c) Comparison with Linear and Piece-wise Linear Systems
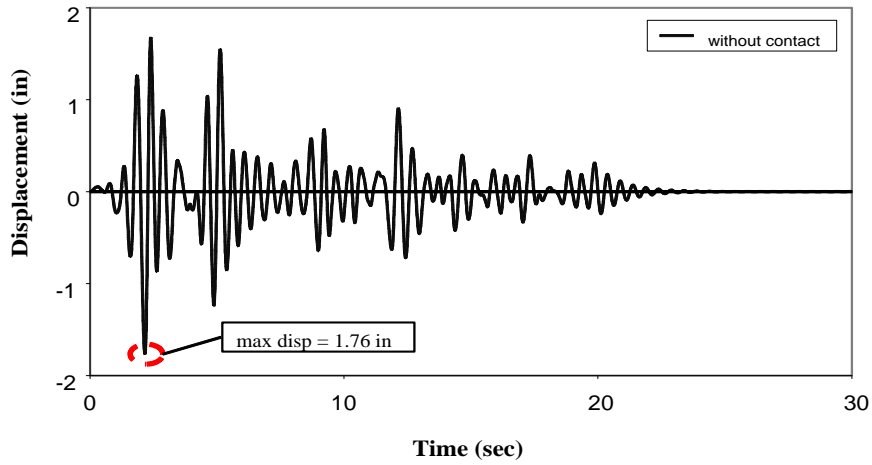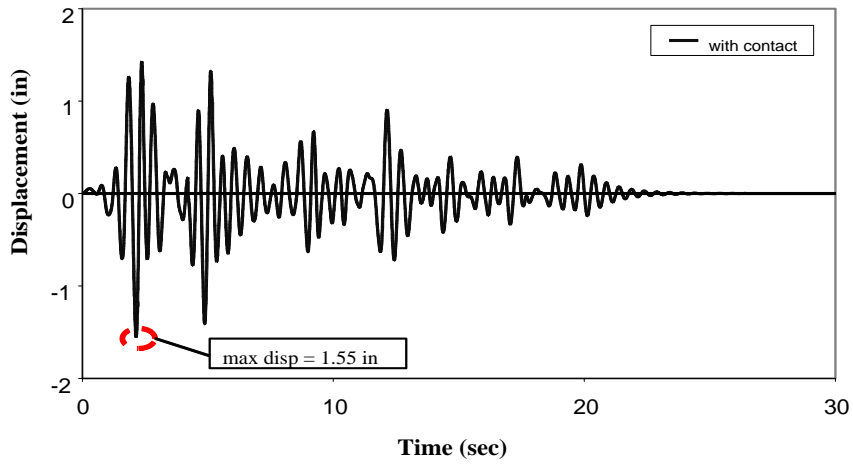

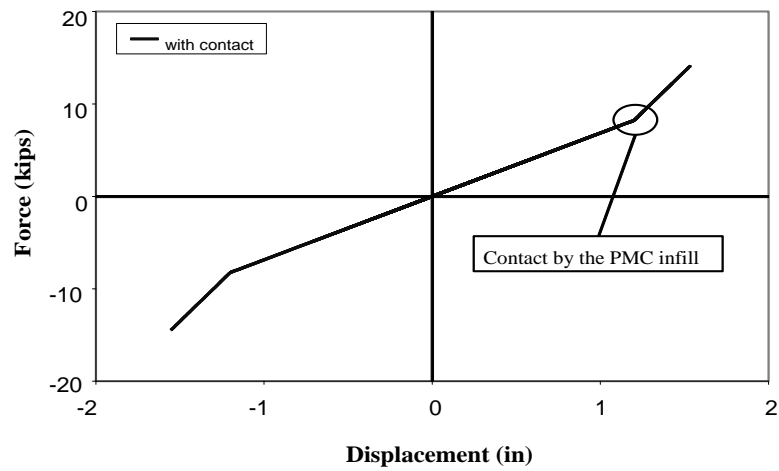(a) Dynamic Response of the Multi-panel PMC Infill System

(b) Force-displacement Response of the Multi-panel PMC Infill System

Fig. 18. Dynamic Response of the Multi-panel PMC Infill Panel System without Contact Mechanism under El-Centro Earthquake Loading
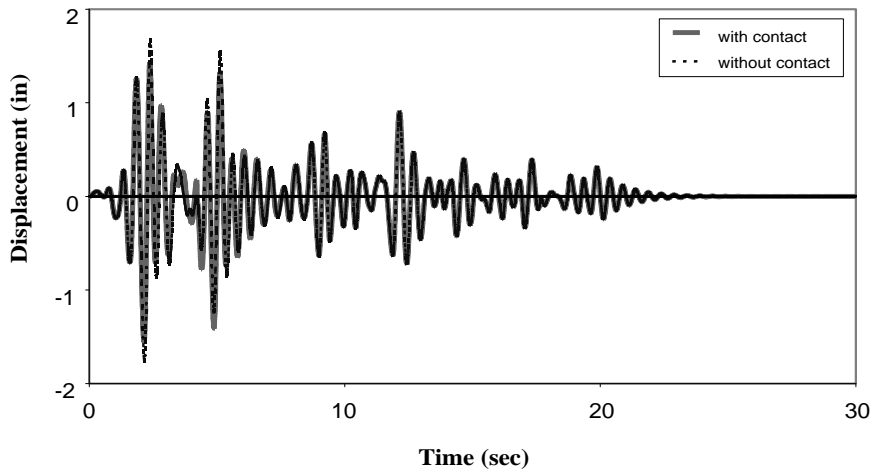
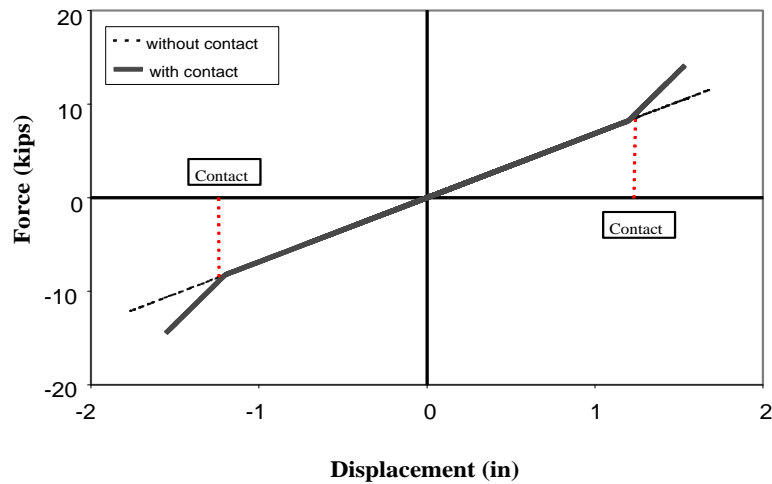(a) Dynamic Response of the Multi-panel PMC Infill System

(b) Force-displacement Response of the Multi-panel PMC Infill System

Fig. 19. Dynamic Response of the Multi-panel PMC Infill Panel System with Contact Mechanism under El-Centro Earthquake Loading

(a) Dynamic Response of the Multi-panel PMC Infill System

(b) Force-displacement Response of the Multi-panel PMC Infill System

Fig. 20. Comparison of Dynamic Response for the Multi-panel PMC Infill Panel System with and without Contact Mechanism of the Infill

VII.   CONCLUSION

This study described the development of a simple SDOF analytical model, which can be used to predict the seismic response in the absence of shaking table tests. This work also provided an effective research tool to study the dynamic properties of the multi panel PMC infill system. To implement the simplified linear and piecewise linear time history analyses, computer programs by MATLAB were developed to carry out the analysis. The convergence was numerically achieved in a number of iterations and appropriate time increments at the turning point of the stiffness.

The conclusions of this study were as followings: by comparing test result from undamped and damped structures, structural damping with passive interface damping layer significantly enhanced the seismic response. Also, for the multi-panel PMC infill system, a piece-wise linear SDOF system was considered in order to the linear SDOF system with two different methods: equivalent linearization method and a piece-wise linear SDOF method. As seen in the result, the response of the equivalent linearized model produced more conservative results in comparison to that of piece-wise linear model using linear restoring spring resistance force. In another word, due to the linear restoring spring resistance force, the piece-wise linear system increased the stiffness and strength after the gaps closed.

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

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