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Cellular-Solid Shear Walls under Seismic Excitations

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ABSTRACT: Cellular solids with deterministic periodic topologies show great potential for applications as response modification elements within structural systems, due to their ultra-light and good thermal properties. Response modification elements can provide additional stiffness and strength, resulting in reduced inter-story drifts and accelerations. A light-weight cellular solid shear wall could work efficiently for vibration mitigation in large scale structural systems. Finite Element models are developed to predict the stiffness, strength, and energy dissipation effectiveness of shear wall panels with cellular solids. The cellular structure of the shear wall essentially eliminates the potential of out of plane buckling which is prevailing in solid steel-plate shear wall systems. In addition, macroscopically, the cellular structure is responsible for the observed pure shear behavior of the panel. A parametric study to quantify the mechanical properties of the cellular shear wall panels is conducted as a function of the thickness and length of the individual cell walls, and the orientation angle of the vertical cell walls. Finally, to evaluate the performance of a structure fitted with cellular shear wall system (CSWS), a model of a three-story structural frame is developed and analyzed under seismic excitation.

INTRODUCTION

Shear wall systems have been implemented by engineers to control displacements by providing additional stiffness to bare frame structures. A lot of innovation has been introduced to increase the ductility of conventional Reinforced Steel Shear Wall (RSSW) system, so as to enrich the energy dissipation performance of shear wall under earthquake excitation.

Steel Plate Shear Wall (SPSW) concept has been developed for the last 25 years and has been studied both analytically and experimentally by Thorburn et al. (1983), Tromposch and Kulak (1987), Caccese et al. (1993), Driver et al. (1998), Berman and Brueau (2003), and Lubell et al. (2000). SPSW system can exhibit high initial stiffness under loading, thus can limit drift effectively. It deforms in a very ductile inelastic manner, thus can dissipate large amount of energy. However, its out-of-plane buckling limits its overall performance.

To eliminate out-of-plane buckling of SPSW, Astaneh-Asl et al. (2004) proposed an innovative composite shear wall (CSW) system, consisting of both steel and concrete plates. CSW was created to mitigate the disadvantage of SPSW (lateral buckling) and of the concrete shear walls (tensional cracking of concrete).

Realizing that the thickness requirement of solid steel plate shear walls is difficult to be met by the steel producers, Vian and Bruneau (2005) suggested using thicker steel plates of low yielding steel (LYS).

Vian and Bruneau (2005) proposed the use of shear wall panels with perforations to alleviate the over-strength concerns of solid steel plate shear walls. In the limit, when the number of perforation is maximized and the size of perforation is minimized, a steel shear wall panel with perforations turns to a cellular-solid shear wall panel (Fig. 1).

The objective of this work is to study the static and dynamic behavior of shear walls with cellular solids. The influence of cell geometry on the behavior of cellular solids, when subjected to monotonic and cyclic shear loading, is investigated.
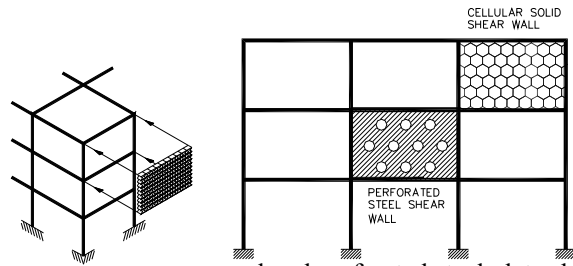

Figure 1.   Cellular-solid shear wall panel and perforated steel plate shear wall panel within framed structural systems.

CELLULAR-SOLID SHEAR WALL SYSTEMS

Utilizing cellular solids to assemble shear wall elements for use in vibration mitigation of large structural systems could offer some advantages over the use of SPSW or CSW systems. Cellular-solid shear wall systems i) are not prone to out of plane buckling as the SPSWs, ii) can offer flexibility to a designer in achieving a balance between stiffness, strength, and ability to dissipate energy, iii) are light weight compared to CSWs, iv) can be utilized as response modification elements, and iv) could be used as architectural elements within a structural system.

Cellular solids are multi-phase composite structures consisting of a solid matrix and a gas matrix. Although the mechanical properties of unit cells are neither isotropic nor homogeneous on their microstructure, the macroscopic behavior of cellular solids is considered homogeneous; given that the cell size is relatively small compared to the size of the structural element consisting of cellular solid. The shape, size, orientation, and geometric properties of a unit cell from a cellular solid influence the mechanical properties of a cellular-solid shear wall.

Figure 1 depicts a cellular-solid shear wall panel within a structural frame. In the present study the regular hexagonal honeycomb cell is considered as a unit cell of the proposed cellular-solid shear walls. A number of shapes based on the regular hexagonal honeycomb cell are explored in studying the behavior of shear wall elements with cellular architecture. Their effect on the strength and energy dissipation properties of shear walls is quantified by analyzing detailed finite element models of a control representative volume element (RVE).

The behavior of a RVE can be used in a homogenization attempt, where an equivalent solid material element can be utilized in the place of the cellular-solid. Therefore for a RVE with a given microstructure and a similar volume element consisting of a homogeneous material, the deformations and forces (strains and stresses) could be defined to be macroscopically equivalent. The RVE, in general, is large in proportion to a unit cell of the cellular solid. This engineering simplification could greatly reduce computational effort and make numerical analysis more efficient when members (shear walls, response modification devices, etc.) consisting of cellular solids are to be used in full scale structural systems.

Furthermore, considering the nature of cellular solids (periodicity) and the aforementioned "homogenization" approximation the behavior of a representative volume element of a cellular material, could be accurately captured by "spring" like hysteretic models.

Modeling of Cellular Solids

The mechanical properties of cellular solids can be described from the geometric parameters of a unit cell and the mechanical properties of the virgin material. The geometric layout of the unit cell, depicted in Figure 2, can be represented by the cell aspect ratio α ($\alpha=h/l$), the internal cell angle θ^o, and the ratio t/l, which is a measure of relative density β ($\beta=C\ t/l$; C=constant).
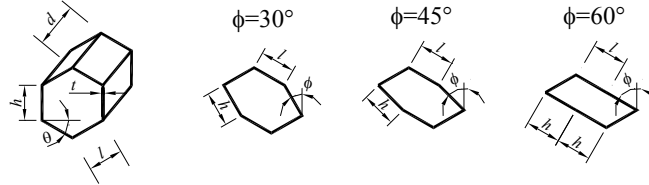

Figure 2. Geometrical characteristics of regular hexagonal honeycomb (for $l=h$ and $\theta=30^o$ regular honeycomb) and honeycomb with vertical walls oriented by angle ϕ.

A regular hexagonal honeycomb cell has an aspect ratio $\alpha = 1$ and an internal cell angle $\theta = 30^o$. Another cellular architecture is considered in this study and shown also in Figure 2. This architecture results from the regular honeycomb when the vertical cell walls of each cell are rotated with respect to vertical direction by an angle ϕ as shown in Figure 2. It should be noted that the sizes of all the cell walls remain the same as shown in Figure 2. This assumption results in a height reduction of each vertical cell wall by ($1-\cos\phi$). This height reduction affects the relative density of the cellular cell. It can be easily shown that the density ratio between the honeycomb oriented by ϕ (ρ_ϕ) with respect to the regular honeycomb (ρ_{RH}) $\rho_\phi/\rho_{RH} = 3/(1+2\cos\phi)$.

Cellular microstructure composed of beam elements have been successfully used for modeling both the linear and nonlinear mechanical properties of cellular materials (Papka and Kyriakides 1994, Overaker et al. 1998). In this work, the ANSYS (2005) software is utilized for the analyses. The element Beam 188 is used for modeling the walls of the cells comprising the RVE. The RVE consists of a 6x9 cell grid as shown in Figure 3. The overall dimensions of the RVE are HxLxd (d is the depth of a cell and of the RVE).
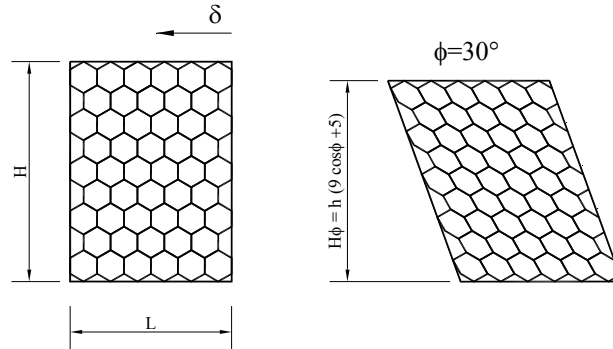

Figure 3. RVE of regular honeycomb cellular solids for $\phi=0^o$ and $\phi=30^{o,}$ consisting of a grid of 6x9 cells.

Estimation of the Mechanical Properties of Cellular Solids

A parametric study to quantify the mechanical properties of the cellular solid (honeycomb-shape) shear wall panels under monotonic shear loading is conducted as a function of the vertical cell wall orientation angle (ϕ), the ratio l/t, and the yield strength of the material. The shear loading is applied as lateral deformation (δ) of increasing amplitude on the top of the RVE (see Figure 3). The ratio of the applied deformation at the top of the RVE over its height is defined as

average shear strain ($\gamma_{aver}=\delta/H_{RVE}$). Similarly, the reaction force at the bottom of the RVE normalized by the cross sectional area of the shear wall panel is defined as the average shear stress of the cellular solid ($\tau_{aver} = F/d/L_{RVE}$). This normalization of the lateral displacements and reaction forces makes the results scalable under the assumptions of the analysis and aids the development of "spring" like hysteretic models for full scale cellular shear walls..

Effect of Orientation of Cell-Vertical-Wall Angle (ϕ)

To demonstrate how strongly the behavior of the cellular solids considered in this study is affected by orientation angle ϕ, a set of finite element models of the RVE are constructed, by varying the orientation angles ϕ between 0 and 60 degrees, and analyzed under monotonic shear deformations.

The cell wall length, thickness, and depth (out of plane dimension) considered throughout this study are l=5.5 mm, t=0.55 mm, and d=0.55 mm accordingly. This choice resulted in an l/t ratio of 10. The material considered is low yield steel (LYS) with properties shown in Table 1. A multi-linear kinematic hardening material model was utilized in the analysis. The effect of cell orientation on the mechanical properties of cellular solids is demonstrated by plots of τ_{aver} vs γ_{aver}.

Figure 4 presents the outcome of the above described parametric analyses. It can be observed that with increasing orientation angle of the cell walls, the yielding stress and the stiffness, both elastic and post yielding, of the RVE increase. The case of ϕ=0 corresponds to regular honeycomb cells and shows the lowest response. The regular honeycomb cell walls are responding in almost pure bending when lateral shear deformation (δ) is applied on the RVE. Under those deformations plastic hinges are forming at the locations where the curvature is the largest (cell wall intersections) as shown in Figure 5. With increased RVE shear deformations the localized plastic hinges propagate away from the cell wall intersections towards the mid-span of the cell walls where the material is still in the elastic range. However, even then, the plastic hinges are still relatively localized and the majority of the material in the cell walls is still elastic. This flexural behavior of the cells is the reason of the mainly elastoplastic behavior of the regular honeycomb RVE under shear monotonic loading.
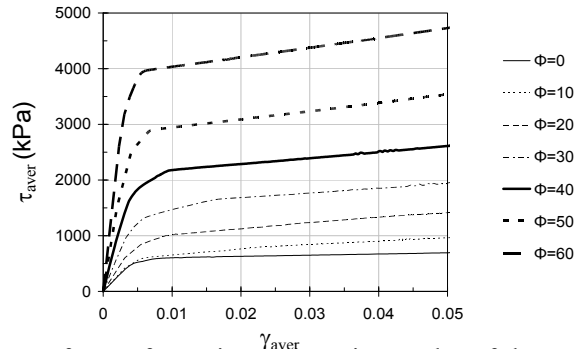

Figure 4. Stress vs Strain response of RVE for various orientation angles of the vertical cell walls of the cellular solid considered in the present study.
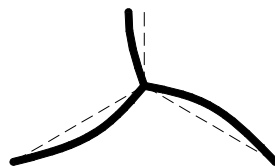

Figure 5. Deformed shape of honeycomb cell wall intersection; deformation shape due to bending behavior when RVE is under pure shear.

For cell orientation angles smaller than 10° the stress-strain relationships are very close to the behavior of the RVE for $\phi=0^o$. For such small angles the cells walls are still experiencing mainly bending response (very little axial deformations are induced to the cells walls). For orientation angles larger than 20° the shear deformations of RVE are manifested as axial deformations in the cell walls resulting in increased stiffness and yielding strength. The increase in yielding strength is due to a more uniform axial yielding along the length of the cell walls and the increased amount of the material that undergoes plastic deformations.

As ϕ increases the mode of deformation of the cell walls now is changing from flexure, as seen in regular honeycombs, to mainly axial deformations. Such uniform axial deformations along the "diagonals" result in an increase of the yield stress and increase of both the elastic and post yielding stiffness of the RVEs. In addition the yield displacement is successively being reduced since bending deformations are eliminated as the orientation angle increases. This behavior indicates that for increased cell orientation angles the cellular solids are expected to dissipate larger amounts of energy and experience larger post yielding stiffness.

Effect of the Yield Strength of Material (Structural Steel vs. Low Yield Steel)
To demonstrate the potential of using a material with higher strength, Figure 6 compares the stress-strain behavior of the RVEs, for cell orientation angle $\phi= 30^o$, between LYS and regular structural steel. The geometry of the cells (*l*, *t*, and *d*) is as indicated previously. Table 1 presents the material properties for the structural steel and the LYS considered in this study. As shown in Figure 4, cellular solids made of structural steel exhibit higher yielding strength and post yielding stiffness, a behavior which is rather expected.

Table 1. Properties of Steel Material

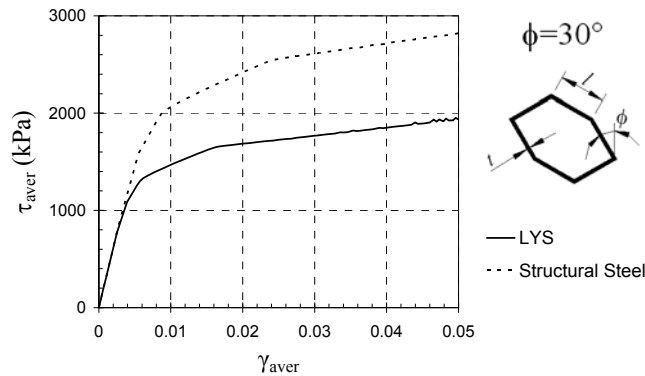|	Young's Modulus (GPa)	Yielding Strength (MPa)	Ultimate Strength (MPa)
Structural Steel	200	250	400
LYS	200	165	345

Figure 6. τ_{aver} vs γ_{aver} curves for two steels

Effect of l/t Ratio
Another factor which affects the behavior of the cellular solids is the ratio (*l/t*), which is related to the inverse of the relative density β ($\beta = C\ t/l$). Figure 7 presents the stress-strain relationship for three values of the ratio (*l/t*) 5, 10, and 20 while the depth of the cell remains constant as presented previously. The pre-yielding stiffness, the yield strength, and the post yielding

stiffness are strongly affected by (*l/t*). Higher values of the (*l/t*) ratio result in an apparent decrease of the density of the cellular solid (the 6x9 cell representative volume element dimensions remains constant). This density decrease results in lower values of all three mechanical properties of interest in this study, since the total volume of material which undergoes plastic deformation is smaller.
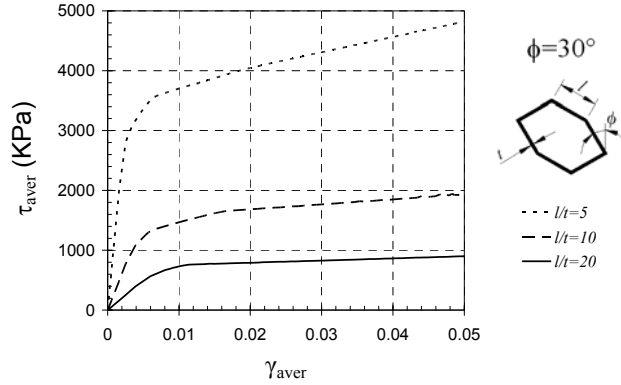

Figure 7. Effect of the *l/t* ratio on the τ_{aver} vs γ_{aver} response of a RVE of cellular solid.

Response of Cellular Solids under Cyclic Loading
The behavior of a RVE of a cellular solid with the vertical walls of regular honeycomb cells oriented by $\phi=30^o$ is studied under cyclic loading. The hysteretic response of such a cellular solid as depicted in Figure 8 is not symmetric. This is due to buckling experienced by a column of cells of the RVE. When the cell walls are under compression, as shown in Figure 8 a number of them buckle. That, in turn, causes the RVE to loose its ability to resist loads through axial actions/deformations. The resulting asymmetric hysteretic behavior is similar to the response of a brace in a braced-frame structure under cyclic loading. Under tension the cell walls yield almost uniformly resulting in stable hysteretic response with significant yielding strength and post yielding stiffness. To achieve a symmetric hysteretic response two cellular-solid shear wall panels with $\phi=30^o$ have to be used side by side or next to each other with the cell wall orientation differing by 90°.
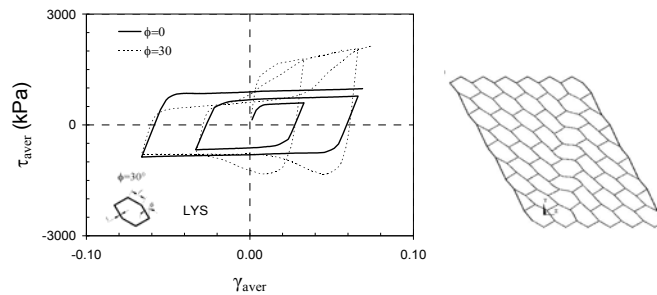

Figure 8. Hysteretic behavior of cellular solids under cyclic loading, and buckling-mode deformations of a column of cells with $\phi=30^o$ when their cell walls are in compression.

In addition, Figure 8 presents the hysteretic response of the RVE for cell angle $\phi=0^o$. The behavior is stable and symmetric because the plastic action is due to flexure with plastic hinging occurring at the cell wall intersections. The yielding strength in this case is almost half of the one experienced by the RVE with $\phi=30^o$, while the post yielding stiffness is almost zero. It is of interest to note that the post buckling behavior of the RVE for $\phi=30^o$ is almost identical to the

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post yielding strength of the regular honeycomb RVE. This is not a coincidence. It appears that after the loss of the axial resistance (buckling) of the cell walls of a column of cells of the representative volume element, rotations of the cell wall intersections are induced throughout the RVE.

The plastic capacity of the cell wall intersections, when these rotations take place, results in a post buckling strength of the RVE with $\phi=30^o$ which is almost identical to the post yielding strength of the RVE with $\phi=0^o$. That is not surprising since the flexural deformation mode which activated throughout the RVE after the buckling of the column of cells is the flexural deformation mode of the RVE with $\phi=0^o$ under pure shear.

RESPONSE OF A 3-STORY FRAME WITH CELLULAR-SOLID SHEAR WALLS UNDER SEISMIC EXCITATION

To evaluate the performance of a structure fitted with cellular solid shear walls (CSSW), a comparison between a three-story three-bay structural frame with and without cellular solid shear wall panels is explored under seismic excitation using the El-Centro wave record. Table 2 lists the structural system properties, and Figure 9 depict the geometry of the 3-story 3-bay frame as well as the shape of the cells in the cellular-solid shear wall (regular honeycomb $\phi=0^o$).

Table 2 Frame System Parameter

Floor #		Section	Total Weight
1st Floor	Beam	W24x62	2900KN
2nd Floor	Beam	W21x50	2900KN
3rd Floor	Beam	W18x46	1500KN
All floors	Column	W14x211	

Table 3 Equivalent Hysteretic Spring Element Parameter

Displacement (m)	Force (KN)
0.01	100
0.10	150
>0.10	150

The shear wall panel under shear deformations can be modeled using a single hysteretic spring element. The force-displacement relationship of this simplified spring element is specified by the parameters shown in Table 3. These parameters approximately correspond to a shear wall of plan dimensions 8.2 x 4.4 m which is made of a cellular material with thickness of 1.0 cm and with the cell sizes l=5.5 mm, and t=0.55 mm. The material the cells are made of, is LYS with properties shown in Table 1.

The 3rd story responses in terms of drift, shear force and CSSW force are presented in Figures 10 and 11. It is observed that the story drift and the story shear were reduced due to the energy dissipation ability of the CSSW system.
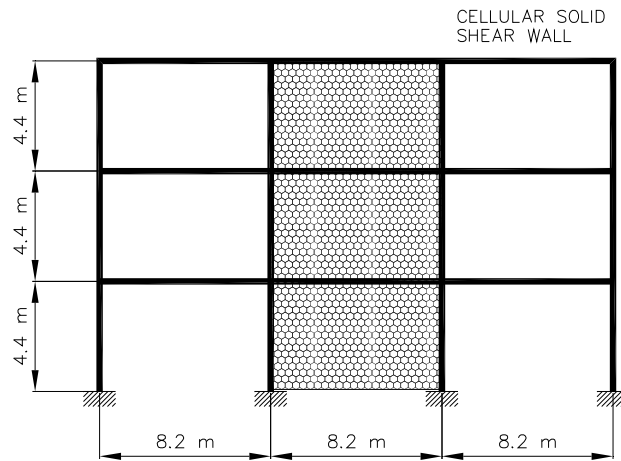
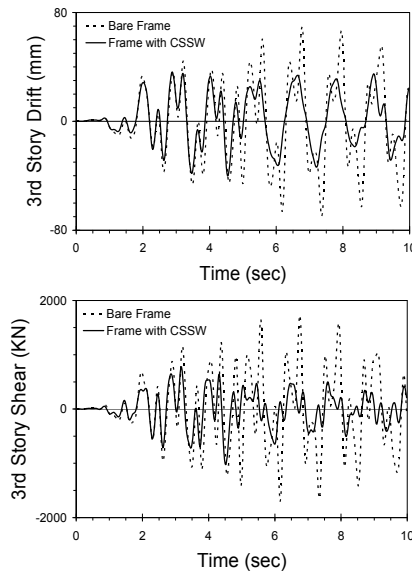Figure 9 Overall dimensions of the 3rd-floor 3-bay frame utilized in the analysis.

Figure 10. Comparisons between the bare frame and the frame with CSSW of 3rd floor drift and 3rd floor shear time histories under El-Centro seismic motion
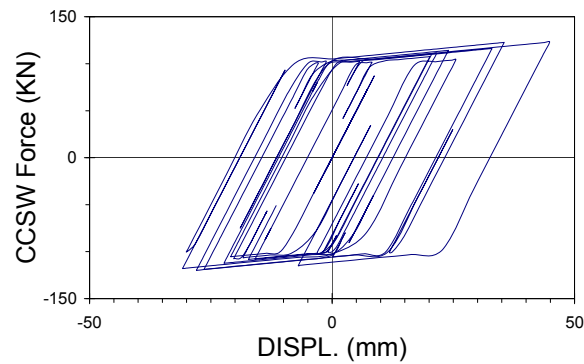

Figure 11. CSSW Force vs 3rd story drift hysteretic response under El-Centro seismic Motion.

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CONCLUSION

An innovative, potentially, light-weight shear wall panel was proposed which could provide stiffness, strength, as well as energy dissipation capacity in structural systems for seismic hazard mitigation design.

Steel plate shear walls are underutilizing material since yielding occurs, by development of diagonal tension field action, to only a fraction of the material the steel plate shear wall is made of. Compression buckling of the plate in the orthogonal direction of the tension field action renters the remaining part of the material of the steel plate (the diagonal strips where out of plane buckling occurs) inactive. The Cellular-Solid Shear Wall system takes advantage of the cellular architecture to induce uniform plastic deformations throughout the area of the shear wall panel, thus maximizing the volume of the material undergoing plastic deformations.

Cellular-Solid Shear Walls can be considered as perforated steel plate shear walls with various shape and size holes. It was shown, that they can be utilized to alleviate over-strength concerns associated with the design of solid steel plate shear walls.

The behavior of Cellular-Solid-Shear walls can be influenced by a number of parameters such as, l/t ratio, material properties, cell shape, cell architecture, and cell orientation angle. As a result an engineer has a large number of parameters in their disposal to use in order to optimize the design of a shear wall that meets strict criteria.

The effectiveness of the shear walls made of cellular-solids was shown from the comparison of the responses of a three-story three-bay steel frame under the seismic motion of El-Centro.

ACKNOWLEDGEMENTS

REFERENCE

Ansys Inc. (2004). Ansys V8.1 Users Manual

Astaneh-Asl, A., & Zhao Q. 2004, Cyclic Behavior of Traditional and Innovative Composite Shear Walls. J. Struct. Engrg. 130(2): 271-284.

Berman, J.W. & Brueau, M. 2003 Experimental Investigation of Light-Gauge Steel Plate Shear Walls for Seismic Retrofit of Buildings. Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, State University of New York. Technical Report MCEER-03-0001

Caccese, V., Elgaaly,M., and Chen, R. 1993. Experimental Study of Thin Steel-Plate Shear Walls Under Cyclic Load. J. Struct. Engrg. 119(2): 573-587.

Driver, R.G., Kulak,G.L., Kennedy,D.J.L.,a & Elwi, A.E. 1998a. Cyclic Test of Four-story steel plate shear wall. J. Struct. Engrg. 124(2): 112-120.

Gibson, L. J., Ashby, M. F. 1999. Cellular Solids, Structure and properties. Cambridge University Press.

Lubell, A.S., Prion, H.G.L., Ventura, C.E., & Rezai, M. 2000, Unstiffened Steel Plate Shear Wall Performance under Cyclic Loading. J. Struct. Engrg. 126(4): 453-460.

Overaker, D.W., Cuitino A.M., & Langrana, N.A. 1998. Effect of morphology and orientation on the behavior of two-dimensional hexagonal, Mech. Mater. 29: 43-52.

Papka, S.D. & Kyriakides, S. 1994. In-plane Compressive Response and Crushing of Honeycpmb. J. Mech. Phys. Solids 42(10): 1499-1532.

Ramirez, O.M., Constantinou, M. C., Kircher, C. A., Whittaker, A. S., Johnson, M. W., Gomez, J. D., Chrysostomou, C. Z.. 2001. Development and Evaluation of Simplified Procedures for Analysis and Design of

Buildings with Passive Energy Dissipation Systems. Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo State University of New York. Technical Report MCEER-00-0010.

Thorburn, L. J. 1983. Analysis of Steel Plate Shear Walls. Struct. Engrg. Report No. 107. Dept. of Civil Engrg., Univ. of Alberta, Edmonton, Alberta, Canada. Thorburn, L.J., Kulk, G.L., & Montgomery, C.J. 1983. Analysis of Steel Plate Shear Walls. Struct. Engrg. Report No. 107. Dept. of Civil Engrg., Univ. of Alberta, Edmonton, Alberta, Canada.

Tromposch, E. W. & Kulak, G. L. 1987. Cyclic and Static Behavior of Thin Plate Panel Steel Plate Shear Walls. Struct. Engrg. Report No. 145. Dept. of Civil Engrg., Univ. of Alberta, Edmonton, Alberta, Canada.

Vian, D. & Bruneau M. 2005. Steel Plate Shear Walls for Seismic Design and Retrofit of Building Structures. Multidisciplinary Center for Earthquake Engineering Research, University at Buffalo, State University of New York. Technical Report MCEER-05-0010.