Steel Honeycomb Dampers for Seismic Retrofit of Structures

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Abstract—The purpose of this paper is to investigate the seismic performance of a honeycomb shaped steel hysteretic damper applied to seismic retrofit or strengthening of a structure. Bilinear model of the honeycomb damper was developed based on the nonlinear force-displacement relationship obtained from finite element analysis. The honeycomb dampers were applied for seismic retrofit of a 15-story apartment building designed without considering seismic load and for seismic design of a 3-story moment frame designed with reduced seismic load. The analysis results showed that the honeycomb dampers were effective in the enhancement of seismic-load resisting capacity of the model structures.

Index Terms—Honeycomb, Hysteretic dampers, Seismic retrofit.

I. INTRODUCTION

Honeycomb structure has long been applied as an efficient energy absorbing material in the field of automobile and aviation industries. Gibson and Ashby [1] presented various formulas for hexagonal honeycomb structures such as elastic modulus, Poisson’s ratio, buckling strength, etc. Wang and McDowell [2] investigated the in-plane mechanical properties of the various periodic honeycomb structures including the Young’s modulus, the elastic shear modulus, the Poisson’s ratio, the yield strength in shear and the yield strength under uniaxial loading. Aref and Jung [3] presented the polymer matrix composite (PMC)-infill wall system consisting of two fiber-reinforced polymer laminates with an infill of vinyl sheet foam for seismic retrofit of structures. The experimental and analytical studies demonstrated that the introduction of a PMC-infill wall panel in a steel frame produced significant enhancements to stiffness, strength, and energy dissipation capacity. Alti-Veltin and Gandhi [4] investigated the energy absorption capability of cellular honeycomb with various cell geometries subjected to in-plane compression through numerical analysis. Ju and Summers [5] carried out numerical studies for design of honeycombs having a high shear strength and a high shear yield strain.

This study aimed to validate the effect of a hysteretic damper made of steel hexagonal honeycombs to enhance seismic load-resisting capacity of building structures. To this end the formulas for initial shear stiffness and yield strength of the honeycomb dampers were derived using the cell wall bending model of Gibson and Ashby [1], which were verified by finite element analysis. The hysteretic behavior and energy dissipation capability of the dampers were also investigated. The dampers were applied for seismic retrofit of a 15-story RC moment frame not designed for seismic load, and for seismic design of a newly designed 3-story RC special moment resisting frame. The effectiveness of the dampers were verified by comparing the seismic performances of the structures without and with the dampers.

II. ANALYSIS OF HONEYCOMB DAMPER UNIT

Figure 1 depicts the configuration of a honeycomb damper installed between two floors in a building structure. The damper is expected to yield in shear and dissipates hysteretic energy when it is subjected to shear deformation due to inter-story drift during earthquake. The initial stiffness of a honeycomb damper can be obtained from the force-deformation relationship of unit honeycomb cell subjected to the shear force. Gibson and Ashby derived the force-deformation relationship of a regular hexagonal cell using the wall bending model. In this study the same reasoning was applied to obtain the shear stiffness and strength of a honeycomb damper.

To observe complete behavior of the damper up to failure, finite element analysis was carried out using the program code ABAQUS. Total of 12 honeycomb damper models with different cell sizes and b/h ratios were prepared for analysis, and the dimension of each model is presented in Table 1, where L and H denote the overall horizontal and vertical dimensions of the model, respectively, t is the depth of the honeycomb, and b and h are the thickness and the height of the vertical cell wall, respectively. The b/h ratio, which is considered to be the most important design parameter, was varied from 0.08 to 0.13 at the interval of 0.01. The heights of the vertical cell walls are 16.5 and 25 mm. The dampers are made of mild steel with yield and ultimate strengths of 330 and 510 N/mm², respectively. Figure 2 shows the analysis model with rigid plates attached to the top and bottom of the damper.
Monotonically increasing horizontal shear force was enforced at the top and bottom rigid plates. Both the material and the geometric nonlinearities were considered in the analysis. Shell elements (S4R) were chosen to model the damper based on the fact that the thickness of the cell wall is significantly smaller than the other dimensions. In addition solid elements (C3D8R_8-node brick, and C3D20R_20-node brick) with 8 and 20 nodes were also used to model the damper for comparison. The force-displacement relationships of the damper HD-1 obtained from three different finite element modeling are plotted in Fig. 3, where it can be observed that after the first yield the strength keeps increasing due to strain hardening, and the rate of increase in strength becomes higher in large displacement as a diagonal tension strut is formed across the cells.

The analysis results obtained from the three different finite element models are similar in the elastic regime; however as the deformation increases the strengths obtained using the solid elements become higher than the strength obtained using the shell elements. Based on the analysis results the shell elements, which provided the most conservative force-deformation relationship, were used to model the honeycomb damper.

Figure 4 shows the force-displacement relationships of the twelve analysis models plotted up to the maximum strain of 0.2 (displacement of 30 cm). It was observed that the vertical cell walls yielded first followed by the yielding of the slanted cell walls. It can be noticed in the figure that both stiffness and strength increase as the thickness-to-height ratio (b/h) of the cell wall increases. As b/h ratio increased by 0.01 the stiffness and the strength of the damper increased by 33% and 21% in average, respectively. For the same b/h ratio the difference in the height of the cell wall did not make significant change in the stiffness and the strength as can be observed in the results of the models HD-1 and HD-7, HD-2 and HD-8, etc.

The comparison of the stiffness and the strength of the analysis models shows that the differences in the initial stiffness and the shear yield strength range from 1 to 8% and 7 to 22 %, respectively. The relatively large difference in the prediction of the shear yield strength can also be observed in the study of Ju et al.[6], who attributed the difference to the fact that the simplified modeling of the shear strength of a honeycomb cell provided by the Gibson and Ashby [1] fails to cover the local micro-rotation of cell walls, which induces more local stresses, resulting in a lower strain.

To investigate the hysteretic behavior of the damper, cyclic analyses of the model HD-1 to HD-4 were carried out using the loading protocol for quasi-static cyclic testing recommended in the FEMA 461 [7] and shown in Fig. 6. The target displacement was set to be 30 mm which corresponds to 1% of the story height of a typical apartment building (3m). Fig. 7 depicts the hysteresis curves of the model HD-1 and HD-4, where it can be noticed that all dampers show stable hysteresis curves. The area enclosed in the curve, which indicates the dissipated hysteretic energy, increases as the b/h ratio increases. Fig. 8 shows that the dissipated energy increases as the cumulative displacement and b/h ratio increase.
For seismic retrofit of the analysis model structure, two honeycomb dampers were installed per story in the center frame of the model structure along the longitudinal direction as depicted in Fig. 9. Dampers were installed between two floors using the rigid chevron bracing from 2nd to 9th story where inter-story drifts are relatively large. Based on some trials, it was confirmed that the strength of the retrofitted structure satisfied the design base shear when the shear capacity of the dampers installed in each story was 27.5% of the design base shear, which is 475 kN. The dimension of the damper was determined so that the maximum shear strain of 0.2 was reached at the inter-story drift of 1.5 % of the story height. The total width and height of the damper were determined to be 1,067mm and 198 mm, respectively, and the height and the thickness of each cell wall are 22mm and 2.9 mm, respectively. The depth of the damper was determined as 100mm. Using Eq. (11) to (15) the initial and the post-yield stiffness are computed as 159.19 and 17.51 kN/mm, respectively, and the yield and ultimate strength are 237.37 and 751.10 kN, respectively.

The bi-linear behavior of the honeycomb damper was modeled using the ‘Rubber Type Seismic Isolator Element’ in the Perform 3D. Fig. 10 shows the pushover curves of the structure along the longitudinal direction before and after the retrofit. It can be observed that both stiffness and strength of the model structure increased significantly as a result of the damper installation. It was observed that plastic hinges first formed at the middle story beams and spread to the beams in the nearby stories, as observed in the structure before retrofit.

Nonlinear dynamic analyses were carried out using the seven earthquake records provided in the Pacific Earthquake Engineering Research (PEER) Center NGA Database. The characteristics of the records are presented in Table 5. Fig. 11 shows the time histories of the top story displacements of the structure before and after the retrofit obtained from the analysis. It can be observed that in most cases both the maximum displacement and the permanent displacement decreased due to the installation of the dampers. Fig. 12 depicts the hysteresis curve of the damper located in the second story during Kobe earthquake, where it can be observed that the dampers experienced many cycles of full yielding, dissipating large amount of seismic energy...
IV. CONCLUSION

The honeycomb dampers were applied for seismic retrofit of a 15-story RC moment frame building and for alternative seismic design of a 3-story moment frame. The analysis results of the model structures using seven earthquake records showed that the honeycomb dampers contributed significantly to the enhancement of the strength and stiffness of the model structure. The nonlinear time history analysis results showed that after installation of the dampers the permanent displacements were significantly reduced. It was also observed that in the structure with honeycomb dampers large amount of energy was dissipated in the dampers resulting in less damage in the structural members.

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REFERENCES


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