Seismic Protection of Automated Stocker System by Customized Viscous Fluid Dampers

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***Abstract*—**The hi-tech industries in the Science Park at southern Taiwan were heavily damaged by a strong earthquake early 2016. The financial loss in this event was attributed primarily to the automated stocker system handling fully processed products, and recovery of the automated stocker system from the aftermath proved to contribute major lead time. Therefore, development of effective means for protection of stockers against earthquakes has become the highest priority for risk minimization and business continuity. This study proposes to mitigate the seismic response of the stockers by introducing viscous fluid dampers in between the ceiling and the top of the stockers. The stocker is expected to vibrate less violently with a passive control force on top. Linear damper is considered in this application with an optimal damping coefficient determined from a preliminary parametric study. The damper is small in size in comparison with those adopted for building or bridge applications. Component test of the dampers has been carried out to make sure they meet the design requirement. Shake table tests have been further conducted to verify the proposed scheme under realistic earthquake conditions. Encouraging results have been achieved by effectively reducing the seismic responses of up to 60% and preventing the FOUPs from falling off the shelves that would otherwise be the case if left unprotected. Effectiveness of adopting a viscous fluid damper for seismic control of the stocker on top against the ceiling has been confirmed. This technique has been adopted by Macronix International Co., LTD for seismic retrofit of existing stockers. Demonstrative projects on the application of the proposed technique are planned underway for other companies in the display industry as well.

***Keywords*—**Hi-tech industries, seismic protection, automated stocker system, viscous fluid damper.

I. Introduction

TAIWAN is a critical manufacturing base in the worldwide supply chain of electronics-related hi-tech products such as semiconductor and display panels. This island country is located in an earthquake-prone area on the circum-Pacific seismic belt. Building structures, including manufacturing factories or Fabs, are designed to withstand severe earthquakes in accordance with stringent design codes. Nevertheless, from time to time the hi-tech industries suffer from substantial seismic losses even in moderate earthquakes. Vulnerability of the Fabs to earthquakes is primarily caused by non-structural failure of critical process tools [1]. Many of the facilities could be protected by adequately installing seismic anchorages based on the concept of strength design; whereas, some of them are vibration-sensitive that implementation of anchorages is prohibited or ineffective in protection of the facility or products during earthquakes. Under such circumstances, performance-based design strategies using seismic isolation or energy dissipation are recommended instead.

The Science Park at Southern Taiwan was struck by an earthquake of Magnitude 6.6 on February 6, 2016. The peak ground accelerations recorded at various sites in the Science Park read around 300 gal which is nearly the design intensity required by the building code. The measured peak floor accelerations in the clean rooms ranged from 400 gal to 600 gal, depending on floor elevation and types of structural system. The intensity of this earthquake is the largest ever encountered by the Science Parks established in the past three decades island-wide. The hi-tech industries were, in this event, heavily damaged and suffered from substantial financial loss estimated to be tens of billions US dollars. The loss attributes mainly to the automated stocker systems (STK) from which massive FOUPs or cassettes containing fully processed wafers or glass panels were colliding or shaken off, regardless of the semiconductor or TFT-LCD Fabs. Recovery of the automated stocker system from the aftermath also contributes the main lead time in the overall recovering process back to normal operation. As a result, seeking effective measures for earthquake protection of the STK becomes the highest priority among others in the minimization of seismic risk. This in turn affects the insurance policy and premiums.

Literatures related to earthquake-proof techniques for vibration-sensitive manufacturing tools are rarely available. The pioneer work by Wang et al. [2] investigates the shockproof strategies for automated stocker system in response to lessons learned from the 2010 Chia-Hsien earthquake of Magnitude 6.4. The recorded in-situ ground motion intensity in terms of PGA was 128 gal, about one third of the aforementioned strongest, occurred in 2016. Nevertheless, storage cassettes (CST) were sliding around and colliding with the STK frame, causing fracture of glass panels during the earthquake. A number of CST was even shaken off the STK to make a hideous mess. As an effort to mitigate the seismic responses, they propose to use either diagonal braces or viscous fluid dampers to retrofit the STK frame. A full-scale STK unit (Model D6000) made of aluminum extrusion material with

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4000×3050×7680mm in dimension and 5650 kg in weight was selected as the testing objective. The braces were installed bottom-to-top in all stories of the frame, whereas four dampers were implemented only in the lowest story. Shake table tests showed that, despite lateral displacement of the STK was significantly reduced due to stiffness increase by the diagonal braces, the acceleration response was amplified in comparison with that of the original frame and failed to meet the expected control goal. The STK retrofitted with viscous fluid dampers, on the other hand, also gave a reduced displacement response of the STK but in a less extent as compared with the braced counterpart, and the acceleration was slightly increased in respect to the original STK without retrofit. This scheme also failed to meet the desired seismic performance. Collision of CST with the STK and overhang of the CST on the storage cell were observed in the tests, regardless of retrofitting or not. Another study by Wang et al. [3] tried to strengthen the fixtures of the STK with the raised floor. The poor seismic performance of the STK was suspected to be blamed on the poor detailing of the connectors at the STK-floor interfaces that led to rocking of the STK during earthquakes. The full-scale shake table tests on the STK unit (Type D50) indicated that the overall displacement of the STK was reduced as expected by minimizing the rocking response, however, with the acceleration amplified by nearly 2.5 times.

In contrast to the previous work by Wang et al. [2], [3], we propose to use viscous fluid dampers in a different manner by placing them in between the ceiling and the top of the STK frame where the relative motion is most pronounced and therefore provide the counteracting forces efficiently. With a passive control force on top against the ceiling via an energy dissipative mechanism, the STK is expected to vibrate quietly by simultaneously reducing displacement and acceleration responses. The control force demand on the dampers would be moderate as the perpendicular moment arm down to the floor level is quite long that a small force could generate considerable counteracting moment to the overturning of the STK resulting from earthquakes. As a result, the damper is relatively small in comparison with those for building or bridge applications, and therefore needs to be customized. Component test of the dampers used in the experiment has been carried out. The customized dampers prove to meet the design requirement. A series of shake table tests have been conducted to verify the feasibility of the proposed scheme on a full-scale STK provided by the industry under realistic earthquake scenarios. With encouraging results obtained, the seismic retrofit strategy for STK has been accepted by Macronix International Co., and the retrofit project for existing stockers is underway.

II. Experimental Setup

A. Stocker

Dimension of the STK to be tested is 135.5×44×431cm giving a large aspect ratio of nearly 10 in the short direction (Fig. 1). The skeleton of the STK is made of aluminum extrusion material type A6N01S-T5 with yield stress 206 MPa, Young's modulus 69 GPa, density 2700 kgf/m^3, and Poisson's ratio 0.33. The STK was directly fixed to the surface of the shake table in the tests.

B. Steel Frame

A steel frame of dimension 210 × 210 × 428.8 cm is fabricated to simulate the inter-story response of the Fab and facilitate implementation of dampers as the ceiling (Fig. 2). Made of H-beam, the single story frame is designed to give a 1% story drift ratio under the code specified design earthquake intensity. The frame's footings were fixed respectively onto the corresponding base pier of 43 cm in height on the shake table. Preliminary system identification test indicates fundamental frequency and damping ratio of the frame are respectively 3.06 Hz and 0.3%.

Fig. 1 The stocker

Fig. 2 The steel frame

C. Viscous Fluid Damper

A pair of viscous fluid dampers is to be installed in parallel on top of the STK against the reacting beam extended from the ceiling grid to simulate the site condition in a more realistic manner. Damping coefficient of the linear damper is determined in a previous numerical study [4] to be 5.0 kgf.s/cm for an optimal performance. Component tests with sinusoidal inputs at various frequencies and amplitudes have been conducted to verify adequacy of the customized damper. Test results summarized in Table I indicates the damping coefficients obtained from various testing conditions are no more than 6.4% deviation from the design target. It is well within the allowable deviation of 15% required by seismic code provision. Measured maximum forces are slightly larger than expected for linear dampers as stiffness of the damper increases with the driving frequency.

Fig. 3 Viscous fluid damper on STK

TABLE I
SUMMARY OF COMPONENT TEST RESULTS

Frequency (Hz)	Amplitude (cm)	Target C (kgf·s/cm)	Achieved C (kgf·s/cm)	max. force (kgf)
0.1	5.5		5.09	19.4
0.5	5.5	5	5.32	112.4
1	4.4		5.15	201.1

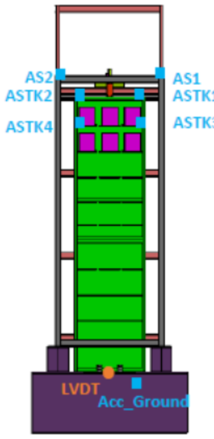
D. Instrumentation

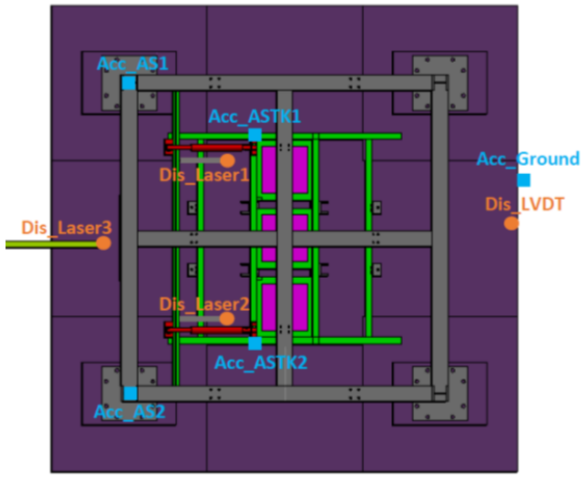
Vibration monitoring sensors including accelerometers (CROSSBOW ± 4g), LVDT and laser displacement sensors were instrumented to trace the achieved ground motion, dynamic responses of the STK and dampers. As indicated in Fig. 4, accelerometers were implemented on the top of the steel frame (AS1, AS2) and the top of STK (ASTK1, ASTK2), as well as the highest shelf (ASTK3, ASTK4) where the FOUPs are housed. Another accelerometer (AG) was placed on the shake table to record the actual ground motion for numerical simulation to be conducted later on. Moreover, an LVDT was installed to measure the ground displacement of the shake table. Two laser displacement sensors (Dis Laser 1, Dis Laser 2) were implemented in between the STK and the reaction beam to measure the damper's stroke. Another laser displacement sensor (Dis Laser 3) was placed between the steel frame and a reference frame outside the shake table. Dis LVDT was adopted to measure the displacement of the shake table simulating the floor excitation. A data acquisition system (IMC) with 16 channels was adopted to take the data at a sampling rate of 100 Hz in the tests.

E. Shake Table and Testing Program

With a payload of 10 tf, the shake table is a uni-axial earthquake simulator driven by an MTS actuator (Model 244.23s) which in turn is regulated by MTS 407 controller for inner loop control along with dSPACE1104A controller for outer loop control to optimize its performance. The 3m × 3m table is a steel boxed case reinforced with ribs to minimize the weight with desired rigidity. Maximal traveling distance of the table is ±12.5cm provided by the displacing capacity of the actuator. The completed experimental setup is shown in Fig. 5.

The earthquake time history considered in the performance tests was 1995 Kobe earthquake. The peak floor acceleration (PFA) was scaled from 150 gal to 700 gal for the tests when implemented with seismic dampers. The PFA of the earthquakes was scaled to 150 gal for testing the original STK without control to avoid possible damage under strong excitations. The time histories recorded were then linearly scaled in accordance with the same PFA of the corresponding case with control for the purpose of comparison.





(a) Side View (b) Top View

Fig. 4 Instrumentation for response monitoring

Fig. 5 STK and frame implemented on the shake table

III. TEST RESULTS

Control performance of the seismic dampers is mainly assessed by response reduction in acceleration at the top of the STK (ASTK1, ASTK2) and the highest shelf (ASTK3, ASTK4), as well as displacement of the STK, in comparison with their uncontrolled counterparts. Dis Laser 1 was set to record relative displacement between the STK and the steel frame (representing the ceiling). The very same relative displacement represents also the stroke of the damper when it is implemented. The recorded time history of damper stroke is to shed light on the dynamic process of the damper during earthquakes and verify if the reserved space in the hydraulic cylinder is sufficient.

Due to limitation of paper length, graphical results are demonstrated only for the scenario of Kobe earthquake with target PFA level of 700 gal. Comparison of peak values for the cases with target PFA levels of 400 gal, 600 gal and 700 gal are summarized in Table II. Completed test results can be found in [5].

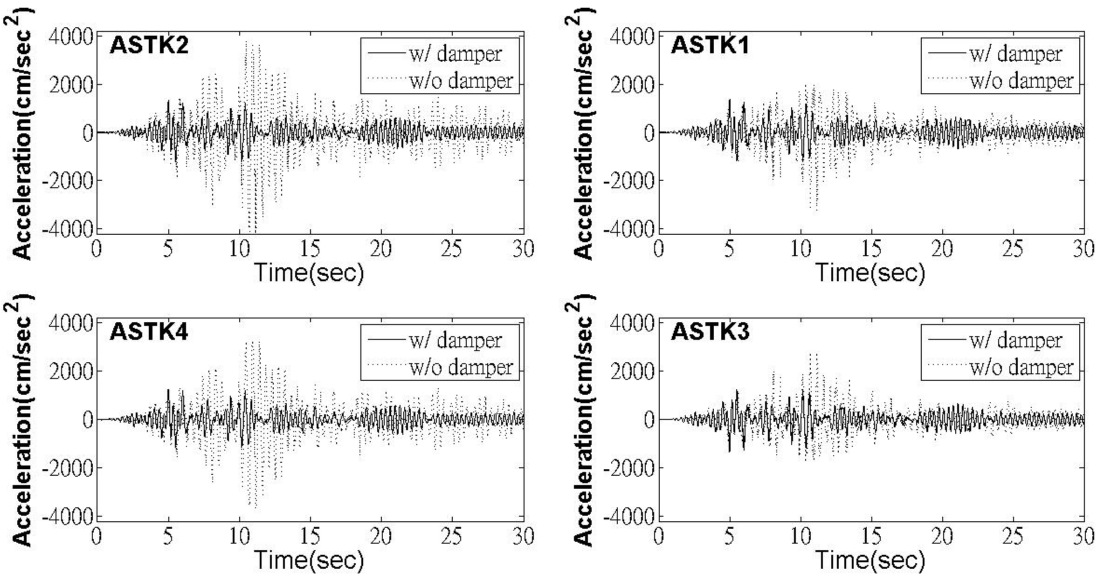


Fig. 6 Comparison of STK acceleration responses (Kobe earthquake, achieved PFA=717 gal)

TABLE II
SUMMARY OF PERFORMANCE TEST RESULTS (KOBE EARTHQUAKE)

Achieved PFA (gal)	sensor	w/o damper	w/ damper	Reduction (%)
		Acc. (gal)	Acc. (gal)	
415	ASTK1	1854.9	877.6	53
	ASTK2	2422.9	916.2	64
	ASTK3	1597.8	852.1	47
	ASTK4	2136.3	897.0	58
	STK Disp.	Dis. (cm)	Dis. (cm)	Reduction (%)
		9.6	7.3	24
614	ASTK1	2747.5	1100.3	60
	ASTK2	3588.9	1108.1	69
	ASTK3	2366.7	1097.7	54
	ASTK4	3164.3	1079.0	66
	STK Disp	Dis. (cm)	Dis. (cm)	Reduction (%)
		14.2	9.8	31
717	ASTK1	3208.1	1377.5	57
	ASTK2	4190.5	1320.7	68
	ASTK3	2763.4	1339.7	52
	ASTK4	3694.7	1226.4	67
	STK Disp	Dis. (cm)	Dis. (cm)	Reduction (%)
		16.6	12.4	25

Fig. 6 shows the comparison of STK acceleration responses, under the achieved PFA of 717 gal, at various positions indicated in Fig. 4. The grey dotted line is for the result without control, while the solid line is for the one with control. Fig. 8 illustrates the time history of damper stroke recorded during the test. The maximum displacement reads 1.2 cm, which is well within the allowable displacing capacity of 5.5 cm reserved for the damper, whereas the solid line is with damper. Evidently all the recorded acceleration responses are remarkably reduced when the STK is controlled with dampers. The acceleration can go as high as 4190 gal when unprotected, and down to 1320 gal if controlled with dampers. The peak reductions in acceleration read from 52% to 68% at different positions, as indicated in Table II. It is worthwhile noting that serious torsional vibration of the STK during earthquakes has been observed as its two sides (ASTK1 vs. ASTK2, ASTK 3 vs. ASTK 4) are not translating equally when unprotected, as one can tell from the grey dotted lines in Fig. 6. The torsional vibration of the STK, however, is minimized when dampers are implemented.

Fig. 7 shows the comparison of the STK displacement (STK disp.) at the top right corner under the achieved PFA of 717 gal. The time history is obtained indirectly by manipulating the recorded results as:

$$\text{STK disp.} = (\text{Laser 3} - \text{LVDT}) - \text{Laser1} \quad (1)$$

where (Laser 3 – LVDT) measures the displacement of the steel frame relative to the shake table, and Laser 1 measures the relative displacement between STK and the frame. The peak displacement is reduced by 25% from 16.6 cm to 12.4 cm when controlled with dampers, as indicated in Table II. The results imply that both acceleration and displacement responses of the STK can be simultaneously reduced by seismic dampers and therefore help reducing the risk of dragging off the FOUPs from the shelves during strong earthquakes. This could not be achieved by using internally bracing the STK with steel bars or dampers as have been attempted by Wang et al. in reference [2].

Table II summarizes the peak responses of the STK in both acceleration and displacement for various target PFA levels from 400 gal to 700 gal. The dampers effectively mitigate both acceleration and displacement responses, regardless of earthquake intensity considered.

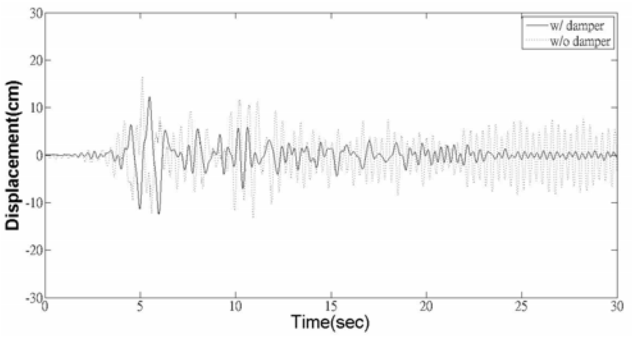


Fig. 7 Comparison of STK displacement (Kobe earthquake, achieved PFA=717 gal)

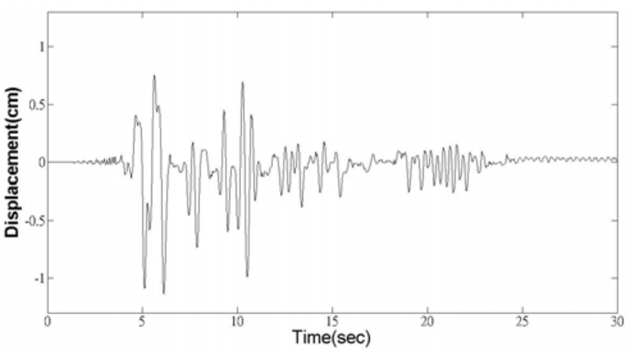


Fig. 8 Time history of damper stroke (Kobe earthquake, achieved PFA=717 gal)

IV. Conclusion

As an effort to seismically retrofit the automated stocker systems for semiconductor and display industries which experienced disastrous damage and financial loss earlier in an earthquake of Taiwan, this study proposes a methodology based on the concept of structural control and experimentally verifies its feasibility. By tactfully placing the viscous fluid dampers on top of the STK utilizing the ceiling as the reaction, one may change the dynamic characteristics of the STK and depress the acceleration and displacement response to a large extent, regardless of the earthquake intensities considered in the tests. The control force and stroke demands on the viscous fluid damper are so moderate that customized small-sized dampers are sufficient in achieving the desired performance. With encouraging test results obtained, Macronix decides to adopt the proposed scheme for seismic retrofit of STK in their Fabs. Numerical simulations under stringent design concerns conducted for Macronix indicate that the maximum control force required by the damper, in the worst condition, is within a few hundred of Newton and the maximum stroke is under 5.0 cm. The project is currently underway and expected to be completed by the end of 2017. This project, by the way, is strongly supported by the insurance company in terms of a good deal on premium discount.

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