SEISMIC RISKS OF TYPICAL DOUBLE FABS IN TAIWAN'S HI-TECH INDUSTRY

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Abstract

This study investigates the potential seismic risks of double fab structures uniquely seen in Taiwan's semi-conductor industry. A typical eight-story double fab structure is considered as the object to explore the seismic vulnerability of such structural systems via computer simulation under realistic earthquake ground motion. As expected, excessive storydrifts are found to be focused on the clean room levels where most of the columns and shear walls have been removed to comply with the manufacturing process. As a consequence, the floor acceleration are amplified and the secondary （P-Δ） effects further deteriorate the earthquake-resisting capability of the fab. As an effort to relieve the soft-story problem, a seismic retrofit strategy by introducing metallic yielding dampers for energy dissipation has been proposed in this study. The metallic yielding damper proves to be effective in enhancing the seismic performance of double fab structures.

INTRODUCTION

The hi-tech industry in Taiwan has been suffering from unexpectedly great seismic hazard over the past few years despite the earthquake intensities have been considered moderate with PGA=0.10g~0.15g (Lee and Loh, 2000；Brain *et al.*, 1999；SEMICON Taiwan, 2001). The seismic loss is mainly attributed to damage or dislocation of the process tools（e.g. the vertical diffusion furnaces with slender quartz tubing, the ion implanter with fragile supporting insulators, and the photolithography stepper, et al.）and the raised floor, with a subsequent operation interruption. Moreover, pounding of the main fab with its adjacent support building and the accompanying failure of the extension joint in between has been observed in typical wafer fabrication plants. Seismic protection has now become a critical issue in not only the hi-tech industry but also the industrial insurance business who has experienced lessons for underestimating the seismic risks. Since the 1999 Chi-Chi earthquake, insurance companies have been increasingly raising the premium and/or pay-by-client percentage of the claim-of-loss while mandate the clients to conduct rigorous seismic retrofit programs as a prerequisite in the contract.

Among various types of wafer foundry plants, the double fabs have shown to suffer much greater

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damage to manufacturing tools and subsequent economic loss than standard fabs of equivalent scale, as observed in the past events. Common structural layout for standard fabs is like this: the first two stories of the fab are generally reinforced concrete structures with heavy shear walls and closely spaced columns（center-to-center column spacing of 3.6m or 4.8m）. Moreover, the deep and stiff waffle slab with holes on the surface panels is built for ventilation purpose and high rigidity demands. Framing above the waffle slab are long span steel mega trusses supported by braced steel frames at the periphery of the plant to reserve a considerably column-free space for manufacturing process. In response to a rapid growth of product demands or a strategic business planning of the incorporation, double fab structures are uniquely seen in Taiwan's semi-conductor industry restricted by the shortage of land resources of Taiwan. Unlike the standard fab (Fig.1(a)) whose cleanroom supports only a relatively light roof level, double fab structures (Figure 1(b)) contain two cleanrooms where most of the columns have been removed to comply with the manufacturing process, which must carry considerable gravity load and seismic lateral load transmitted from the stories above. As the plan area of today's hi-tech fab has been increasingly wider, it is insufficient to brace only the peripheral frames to maintain rigidity and strength, and soft （and likely weak）stories are inevitably formed at the cleanroom levels. As a result, the double fab structures become seismically vulnerable once encountered with severe earthquakes. Excessive storydrifts are to be focused on the cleanroom levels during the earthquakes. As a consequence, the floor accelerations are amplified and the secondary （P-Δ）effects further deteriorate the earthquake-resisting capability of the fab and exaggerate the seismic hazards. Even if the earthquake is moderate enough to be structurally harmless, the floor acceleration could be amplified and damage the delicate manufacturing tools due to a soft-story configuration. If not prohibited, special care has to be exerted on the earthquake resistant design of double fab structural systems.

In reviewing the structural design reports of some existing double fabs, it is found that some design concepts or considerations have been misled or overlooked. The major controversies include,

(1) Completely following the ductility design suggested by the code

The code specification is adequate for uniform buildings and appeals for minimum requirement only. With two soft stories, the double fab structures are in no way uniform and the designers should be extremely careful in applying the code–specified formula. With extremely stiff waffle slabs and soft stories, the desired strong-column-weak-beam condition does not exist, and logically no plastic hinges will be formed at the beams so that the structure will not behave in a ductile manner at all. Therefore, the reduction factor of the seismic base shear based on the ductility design concept should not be fully accounted for. In other words, by applying the code suggested formula for the design base shear would underestimate the actual seismic loading to a large extent.

(2) Perform static analysis only

The structure is irregular vertically due to the existence of two soft stories. In such circumstances, dynamic analysis is mandatory by the code. Moreover, the torsional response that might cause fatal damage to the structure can only be reflected via time history analyses.

(3) Fail to check the ultimate strength of the story shears, in particular for the soft stories

This design check is also mandatory by the code regardless of the type and height of the structure.

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As the fab structure is often less than 50 m in height, no peer review is mandatory by law. Unfortunately, as the above concerns in the design stage were not aware of and corrected, the seismic risks of double fab structures would be unthinkably higher than one might expect. Serious measures on seismic retrofit of the existing double fab structures are necessitated to eliminate the potential catastrophe in the next “big shock” while mitigating seismic loss in occasional moderate events.

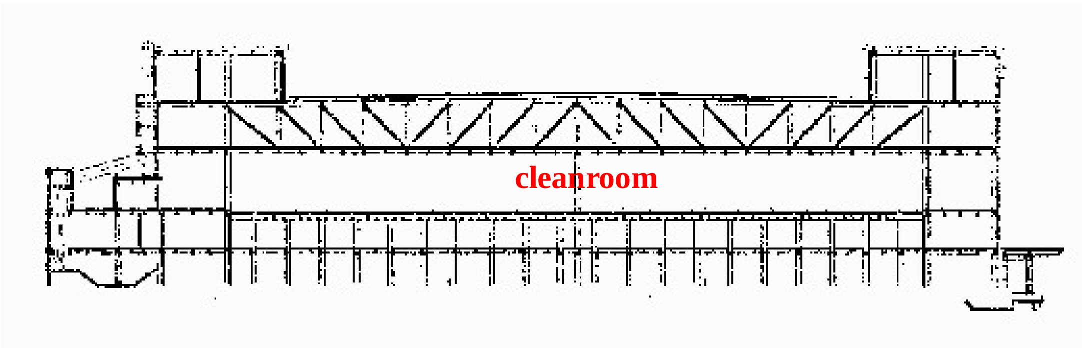

Figure 1(a) Standard fab

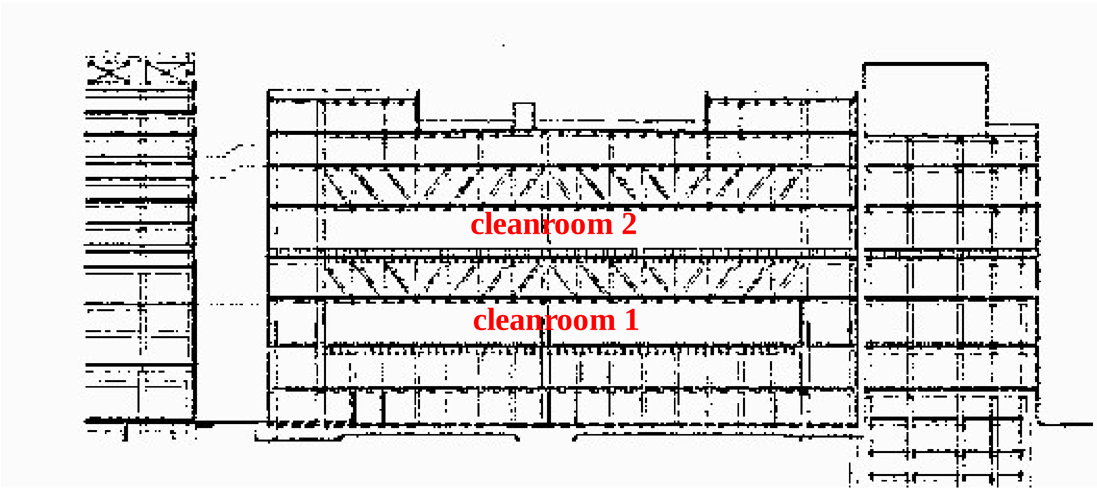

Figure 1(b) Double fab

Modern earthquake protection techniques discard the traditional idea of economy-based (ductility) design for a performance-based design concept emphasizing the maintenance of structural integrity even under exceptionally severe earthquakes. Advances in the development and practical implementation of passive energy dissipation devices for earthquake protection and retrofit of structures have been achieved in recent years (Housner, *et al.*, 1997；Soong and Dargush, 1997；Soong and Spencer, 2002). The control forces imparted from the passive control devices are developed in response to the vibration of the structure without external power supply. Among numerous energy dissipation devices available the most widely adopted are the metallic yielding damper, VE damper and fluid damper, et al. The first is displacement-dependent while the others are velocity-dependent. Both types of dampers are functionally competitive. However, in view of long term usage and reliability, the metallic yielding dampers (working by transverse bending) are preferred for

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maintenance-free (no leakage problem), temperature-independent (VE damper is temperature-dependent) and less demanding in alignment precision （compared with axially loaded fluid dampers）. The feasibility of employing the metallic yielding dampers for seismic retrofit of a specific double fab structure will be explored in this study. The earthquake ground acceleration recorded at the TCU017 station by Central Weather Bureau, Taiwan during 921 earthquake is considered representative of the site characteristics in Hsinchu Science-Based Industrial Park （HSBIP）area where the objective structure is located. It will be used for seismic performance assessment.

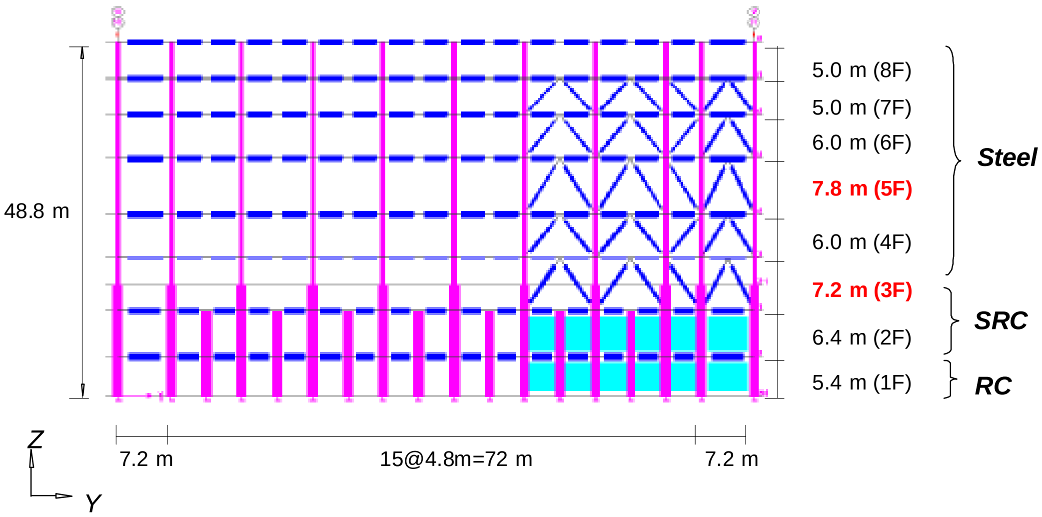

Figure 2(a) Elevation view of the peripheral frame (short direction)

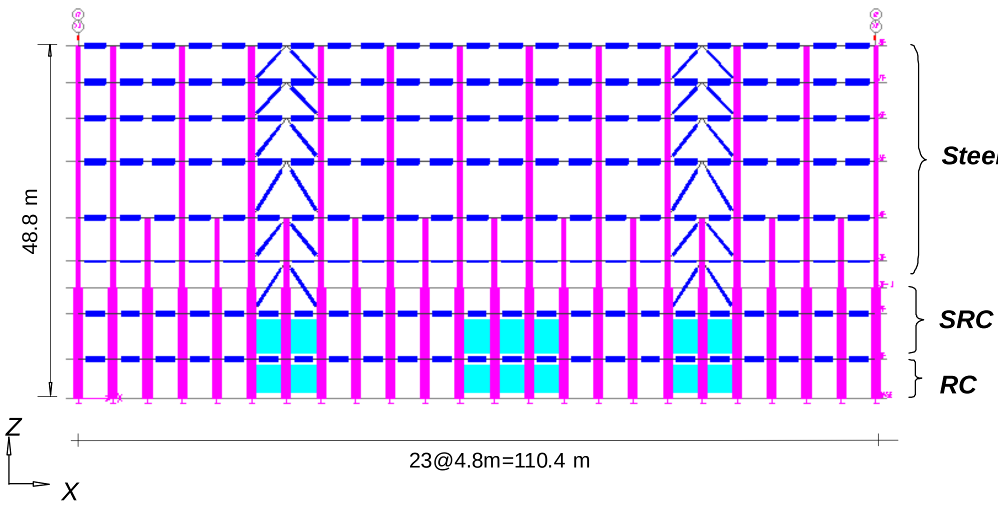

Figure 2(b) Elevation view of the peripheral frame (long direction)

SEISMIC PERFORMANCE ASESSMENT OF A TYPICAL DOUBLE FAB STRUCTURE

The Target Fab Structure

The seismic performance of the existing eight-story double fab （Figure 2）containing two cleanrooms

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in the 3rd and 5th floors, respectively, as illustrated, is to be assessed. With $110.4m \times 86.4m$ in plane dimension and $48.8m$ in height, the double fab structure consists of reinforced concrete (RC) from ground level to the second floor, steel and reinforced concrete (SRC) from the second to the third floor, and steel frame above. The floor masses considered in the analytical model include those of the raised floor and manufacturing tools provided by the owner. The plane and three-dimensional views of the fab building are shown in Figure 3 and Figure 4, respectively.

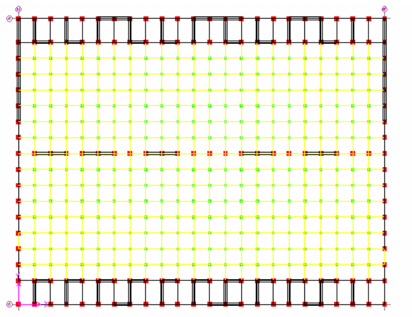

Figure 3(a) Structural plans at 1~2 F

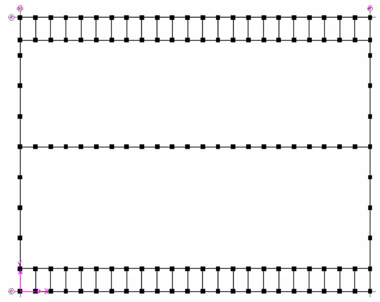

Figure 3(b) Structural plans at 3F and 5F (Clean Rooms)

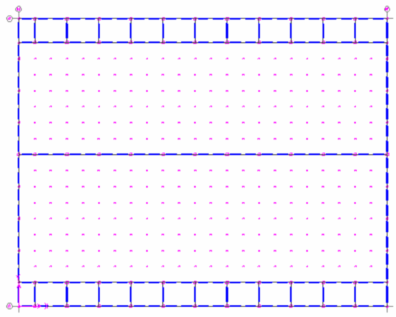

Figure 3(c) Structural plans at 4F, 6F and 7F

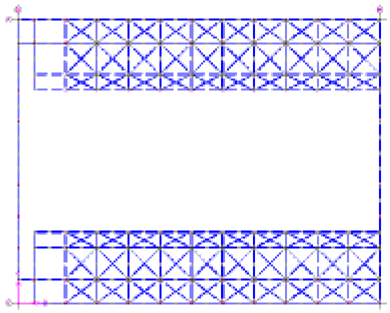

Figure 3(d) Structural plans at roof

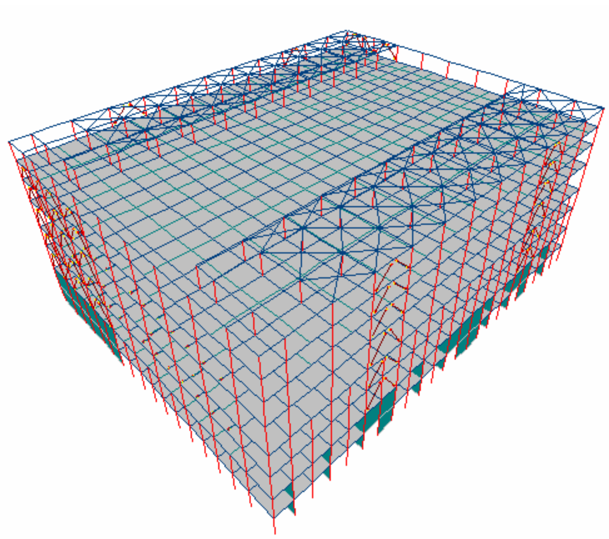

Figure 4 Finite element model of the objective eight-story double fab structure

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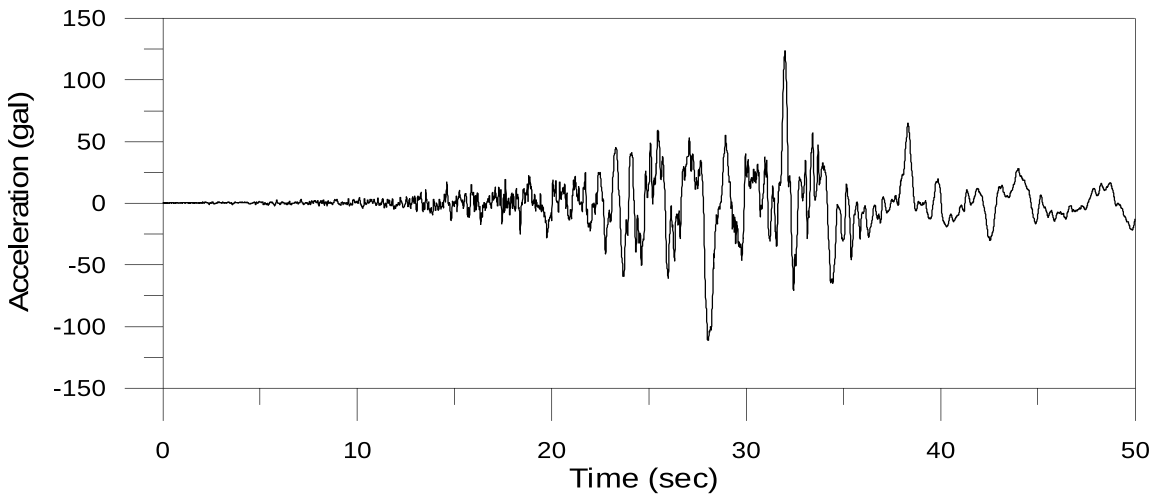

Figure 5 Ground acceleration measured in Chi-Chi Earthquake (TCU017 station, inside HSBIP)

Seismic Performance Indices

As a quick assessment in the preliminary stage, the maximum storydrifts at critical locations of the structure from dynamic time history analysis are considered as a seismic performance index. Storydrift ratio within 0.5% will be considered acceptable under the design earthquake intensity of PGA=0.33g, as regulated by the building code. Moreover, the floor accelerations that are critical to sensitive manufacturing tools will be assessed. Since no specific performance-based design criteria have been suggested up to date, the peak floor acceleration will be compared with those derived from the UBC97 and IBC2000, which has been the design criteria for seismic anchorage of the tools and raised floor.

Moreover, column stress states under the most critical loading combination with additional consideration of P-△ effects will be further examined based on the ASD (Allowable Stress Design) stability interaction equation：

$$\frac{f_a}{F_a} + \frac{f_{bx} C_{mx}}{(1 - f_a / F'_{ex}) F_{bx}} + \frac{f_{by} C_{my}}{(1 - f_a / F'_{ey}) F_{by}} \leq 1.0 \qquad (1)$$

where $f_a = P/A_g$ is the axial compression stress at service load, f_{bx}, f_{by} are flexural stresses at service load based on primary bending moment about the x-axis and y-axis, respectively, F_a is the allowable compression stress considering the member as loaded by axial compression only, F_{bx}, F_{by} are the allowable flexural stresses for the x-axis and y-axis, respectively, considering the member loaded in bending only, and C_m is the moment modification factor.

Simulation Results and Performance Assessment

Assessment of the seismic performance is conducted in two phases. Phase I considers the earthquake intensity of Grade 6 with PGA of the ground motion scaled up to 0.33g to comply with code requirement and phase II considers Grade 7 with PGA=0.50g to explore the seismic risk further in case a rare event occurs.

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Phase I- Performance assessment under PGA=0.33g (Grade 6)

The peak displacement and story drift ratio at/between the floors in both the principal directions are summarized in Table 1. As expected, excessive storydrift ratio （≧0.5%） are found between 3~5 floors in the X (long) direction（when *w/o damper*）, indicating a soft-story phenomenon. The soft-story phenomenon is not found in the Y (short) direction, however.

Table 2 summarizes the peak floor acceleration at the cleanroom levels obtained from the time history analysis and compared with those suggested by UBC97 （$S_a = \frac{a_p C_a I_p}{R_p}\left[1+3\frac{h_x}{h_r}\right]g$） and IBC2000 （$S_a = \frac{a_p (0.4S_{DS}) I_p}{R_p}\left[1+2\frac{h_x}{h_r}\right]g$） based on the commonly adopted values a_p = 1.0; $C_a = 0.4S_{DS} = 0.4$; $R_p = 1.5$; $I_p = 1.25$ for UBC97 and 1.5 for IBC2000. The result indicates the code specified design values for seismic anchorage of facility are somewhat conservative. Nevertheless, this does not warrant damage-free and function integrity of the tools from a performance-based design point of view.

Table 3 shows the maximum internal forces of column C6 (see Figure 8) in the cleanroom 1 level and the stress ratios (in parentheses) under load combination $0.75(DD+LL+EQ)$ obtained by equation (1). The stress ratio of the column （when *w/o damper*）is found to be 1.47 which suggests a damage potential of the column under the design earthquake and implies a weak story of the fab at the cleanroom 1 level.

The above analysis reveals that the objective double fab structure in its present configuration shows a soft and weak story potential under the design earthquake intensity of seismic zone I in Taiwan and suggests necessity for seismic retrofit.

Table 1 Floor displacement and story drift ratio (PGA=0.33g)

Floor	Height (m)	Displacement (cm)				Story Drift Ratio(%)			
		w/o damper		w/ damper		w/o damper		w/ damper	
		X	Y	X	Y	X	Y	X	Y
8	5	20.7	12.7	13.9	7.0	0.42	0.44	0.30	0.22
7	5	18.6	10.5	12.4	5.9	0.40	0.32	0.30	0.18
6	6	16.6	8.9	10.9	5.0	0.40	0.10	0.30	0.07
5	7.8	14.2	8.3	9.1	4.6	0.55	0.44	0.36	0.23
4	6	9.9	4.9	6.3	2.8	0.67	0.13	0.40	0.08
3	7.2	5.9	4.1	3.9	2.3	0.64	0.42	0.40	0.24
2	6.4	1.3	1.1	1.0	0.6	0.13	0.11	0.09	0.06
1	5.4	0.5	0.4	0.4	0.2	0.09	0.07	0.07	0.04

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Table 2 Acceleration at cleanroom floor (PGA=0.33g)

Floor	**Code**		**w/o Damper**		**w/ Damper**	
	UBC97	**IBC2000**	**X**	**Y**	**X**	**Y**
3F	**0.58g**	**0.59g**	0.42g	0.37g	0.39g	0.36g
5F	**0.85g**	**0.81g**	0.82g	0.60g	0.65g	0.44g

Table 3 Maximum internal forces and stress check of column C6 (PGA=0.33g)

Floor	***Height (m)***	***Axial Force (t)***		***Shear (t)***				***Moment (t-m)***			
		w/o Damper	***w/ Damper***	***w/o Damper***		***w/ Damper***		***w/o Damper***		***w/ Damper***	
				X	***Y***	***X***	***Y***	***X***	***Y***	***X***	***Y***
5F	7.8	392	508	125	60	65	35	484	221	257	134
					Stress ratio check			**(0.60)**		**(0.51)**	
3F	7.2	1972	875	252	259	139	169	411	343	223	216
					Stress ratio check			**(1.47)**		**(0.74)**	

Table 4 Floor displacement and story drift ratio (PGA=0.50g)

Floor	***Height (m)***	***Displacement (cm)***				***Story Drift (%)***			
		w/o USD		***w/ USD***		***w/o USD***		***w/ USD***	
		X	***Y***	***X***	***Y***	***X***	***Y***	***X***	***Y***
8	5	31.4	19.2	21.5	10.5	0.64	0.67	0.48	0.32
7	5	28.2	15.9	19.5	8.9	0.61	0.48	0.46	0.28
6	6	25.2	13.5	16.8	7.5	0.61	0.15	0.48	0.08
5	7.8	21.5	12.6	13.9	7.0	0.84	0.66	0.54	0.36
4	6	15.0	7.4	9.7	4.2	1.01	0.20	0.62	0.12
3	7.2	8.9	6.2	6.0	3.5	0.97	0.63	0.63	0.36
2	6.4	2.0	1.7	1.5	0.9	0.19	0.17	0.16	0.09
1	5.4	0.8	0.6	0.5	0.3	0.14	0.11	0.09	0.06

Table 5 Floor acceleration (PGA=0.50g)

Floor	**Code**		**w/o Damper**		**w/ Damper**	
	UBC97	**IBC2000**	**X**	**Y**	**X**	**Y**
3F	**0.58g**	**0.59g**	0.64g	0.56g	0.59g	0.55g
5F	**0.85g**	**0.81g**	1.24g	0.92g	1.00g	0.67g

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Table 6 Maximum internal forces and stress check of column C6 (PGA=0.50g)

Floor	***Height (m)***	***Axial Force (t)***		***Shear (t)***				***Moment (t-m)***			
		w/o Damper	***w/ Damper***	***w/o Damper***		***w/ Damper***		***w/o Damper***		***w/ Damper***	
				X	***Y***	***X***	***Y***	***X***	***Y***	***X***	***Y***
5F	7.8	596	776	190	91	100	53	736	336	389	205
						Stress ratio check		**(0.80)**		**(0.77)**	
3F	7.2	2997	1331	383	394	210	253	625	521	337	332
						Stress ratio check		**(2.07)**		**(1.11)**	

Phase II- Performance assessment under PGA=0.50g (Grade 7)

As the earthquake intensity further amplified to 0.5g, excessive story drifts have been found not only at the cleanroom levels （both X and Y directions）but the stories above (X direction), as summarized in Table 4. The soft-story phenomenon is observed in both the principal directions of the fab now. Moreover, the floor accelerations at the cleanroom 2 level have shown, in Table 5, to exceed the design values （based on PGA=0.4g）in the long direction.

Table 6 shows the maximum internal forces of column C6 (see Figure 8) in the cleanroom 1 level and the stress ratios (in parentheses) under load combination $0.75(DD+LL+EQ)$ obtained by equation (1). The stress ratio of the column （when *w/o damper*）is found to be 2.07 which suggests a even higher damage potential of the column than under the design earthquake and deteriorates the weak story problem further.

RETROFIT OF THE DOUBLE FAB WITH METALLIC YIELDING DAMPERS

Metallic Yielding Damper

The metallic yielding damper is an earthquake protective device that dissipates earthquake energy through inelastic deformation of the steel plates. Each of its steel plates is tailored into an optimum shape （X-shape）to maximize its energy dissipative capacity. The damper can be designed to yield at moderate deformation so as to protect the structure at early stages. If the dampers are tactfully sized and allocated, both the acceleration and displacement responses of the structure can be simultaneously reduced during severe earthquakes. Discarding a commonly adopted welding process, the unit could be assembled by bolting together the steel plates with a set of threaded rods, thus improving the manufacturing process while making it more compact than its welded counterpart. This type of damper is durable, temperature-independent, and maintenance-free. It is considered one of the most cost-effective of all commercially available seismic dampers. The yielding displacement and the stiffness of each X-shape steel plate are presented respectively as (Whittaker *et al.*, 1991；Arturo, 1997):

$$\Delta_y = \frac{s_y h^2}{2Et} \tag{2}$$

and

$$k_d = \frac{2EBt^3}{3h^3} \tag{3}$$

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where s_y is the yielding stress of the steel plate, E is the young's modulus, h and t are the height and the thickness of the steel plate, respectively, and B is the width of the taped steel plate at the fixed ends. The desired yielding displacement and stiffness of the damper can be achieved by adjusting the dimensions of the height, width and thickness of the steel plate. For a damper with n steel X-shape plates in parallel, the yielding displacement is the same as described by equation (2), while the elastic stiffness of the damper can be modified as：

$$k_D = \frac{2nEBt^3}{3h^3} \quad (4).$$

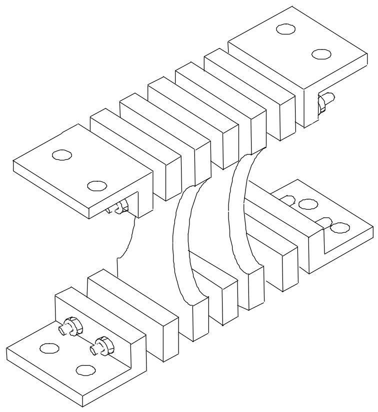

Figure 6 Metallic yielding damper

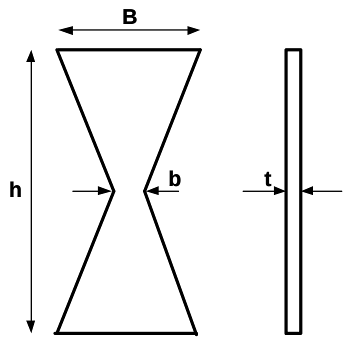

Figure 7 Taped structural steel plate

Seismic Performance Assessment of The Retrofitted Double Fab

To improve the seismic performance of the double fab and prevent it from damage during earthquakes of 475-yr return period. Since the sub-fab levels (1~2F) has been very stiff with closely spaced columns and shear walls, the dampers are allocated above 3F to 5F at the peripheral frames, as illustrated in Figure 8, to maximize its torsion-resisting effect. Totally 90 sets of identical dampers (22 sets in 3F, 34 sets in both 4F and 5F) with a capacity of 112-ton designed to yield at a deformation of 0.7 mm corresponding to a 50-ton yielding load are implemented.

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The seismic performance of the double fab, under the design earthquake intensity (PGA=0.33g), evidently has been improved after retrofit with metallic yielding dampers as the storydrift ratios of all the stories have been controlled within the allowable level, as indicated in Table 1. Moreover, the floor acceleration can be reduced for more than 20% in the cleanroom 2 level (see Table 2) and the bi-axial stress ratio of column C6 at the cleanroom 1 level has been reduced to 0.74, suggesting elimination of the damage potential. The comparisons of displacement and acceleration time histories (3F & 5F) are illustrated in Figure 9(a) and Figure 9(b), respectively.

As the earthquake intensity increased further to 0.5g, the seismic performance of the retrofitted structure exhibits superiority to the original one. The comparisons of displacement and acceleration time histories (3F & 5F) are illustrated in Figure 10(a) and Figure 10(b), respectively. Nevertheless, the soft-story phenomenon in the X direction still is not completely eliminated with the current amount of dampers. Moreover, in spite the bi-axial stress ratio of the column has been reduced for approximately 50% (from 2.07 to 1.11), damage of the column in this earthquake intensity level is still inevitable. More dampers are desired for further improvement of the seismic performance.

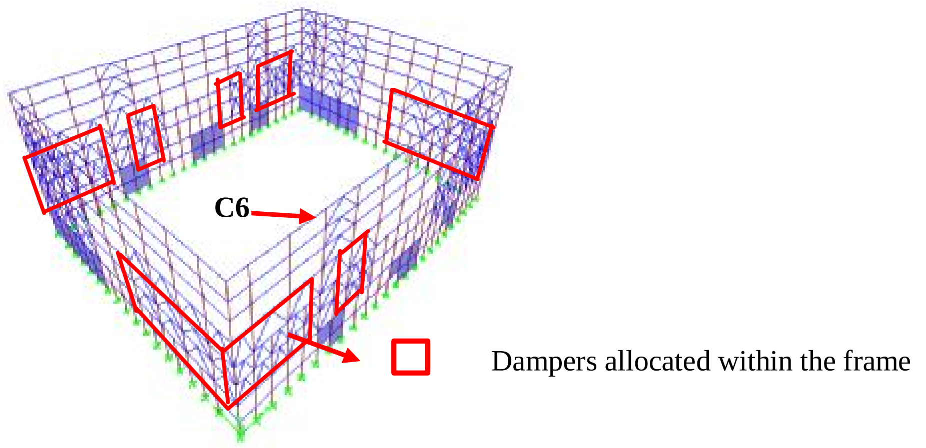

Figure 8 The implementation of the metallic yielding damper scheme in the Fab

Figure 11 illustrates energy dissipation capability of the metallic yielding dampers for various earthquake intensities.

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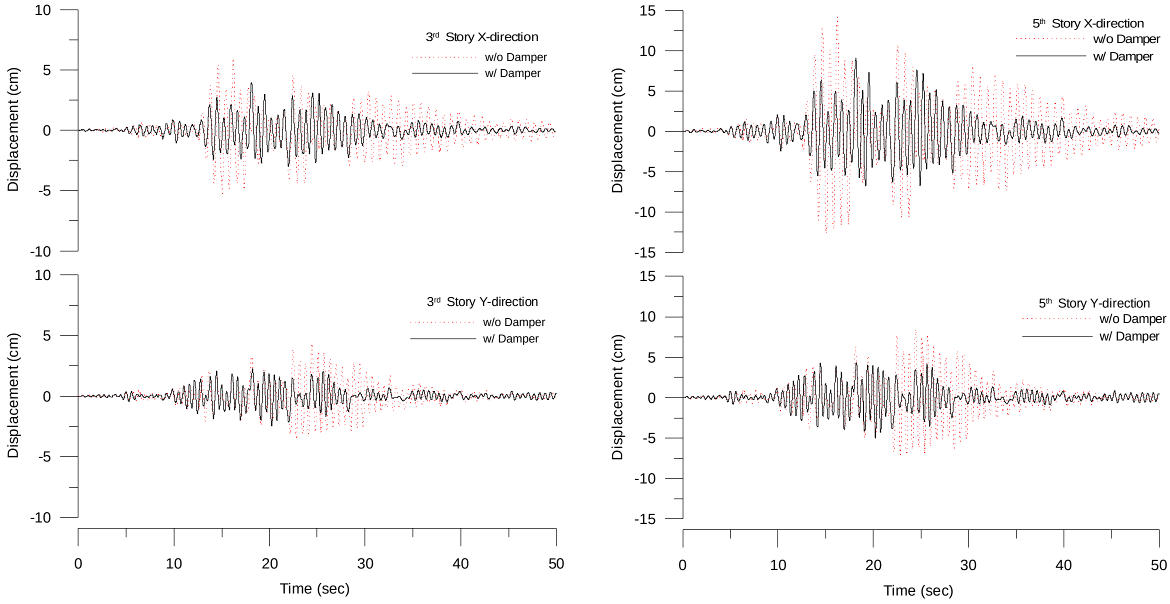

Figure 9(a) Comparison of displacement responses (3F & 5F)-PGA=0.33g

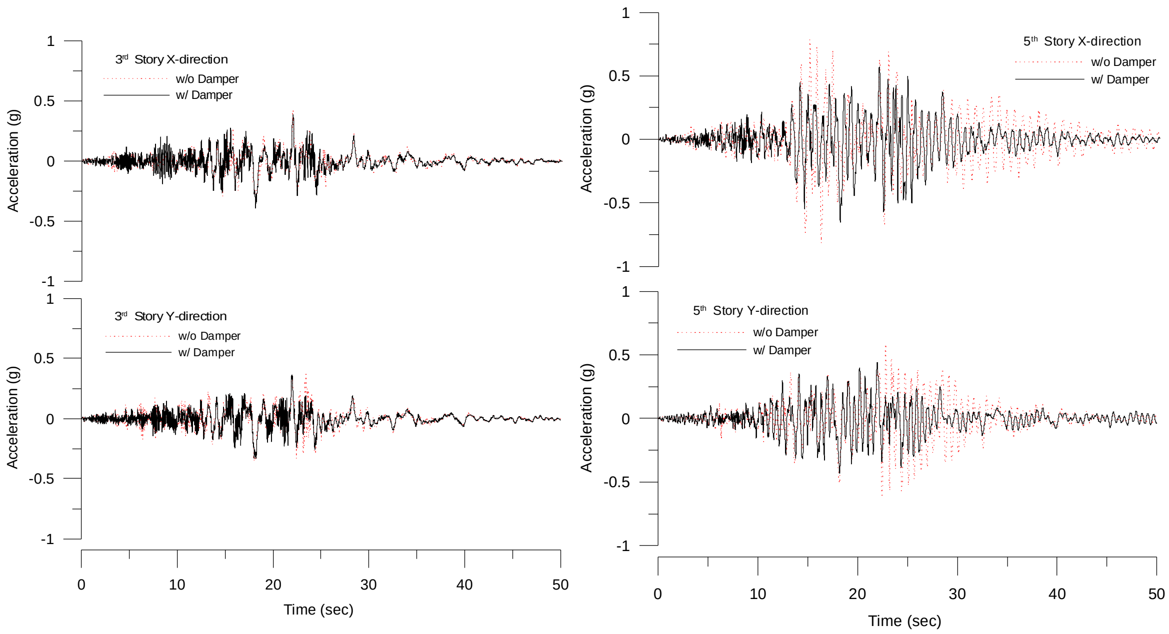

Figure 9(b) Comparison of acceleration responses (3F & 5F)-PGA=0.33g

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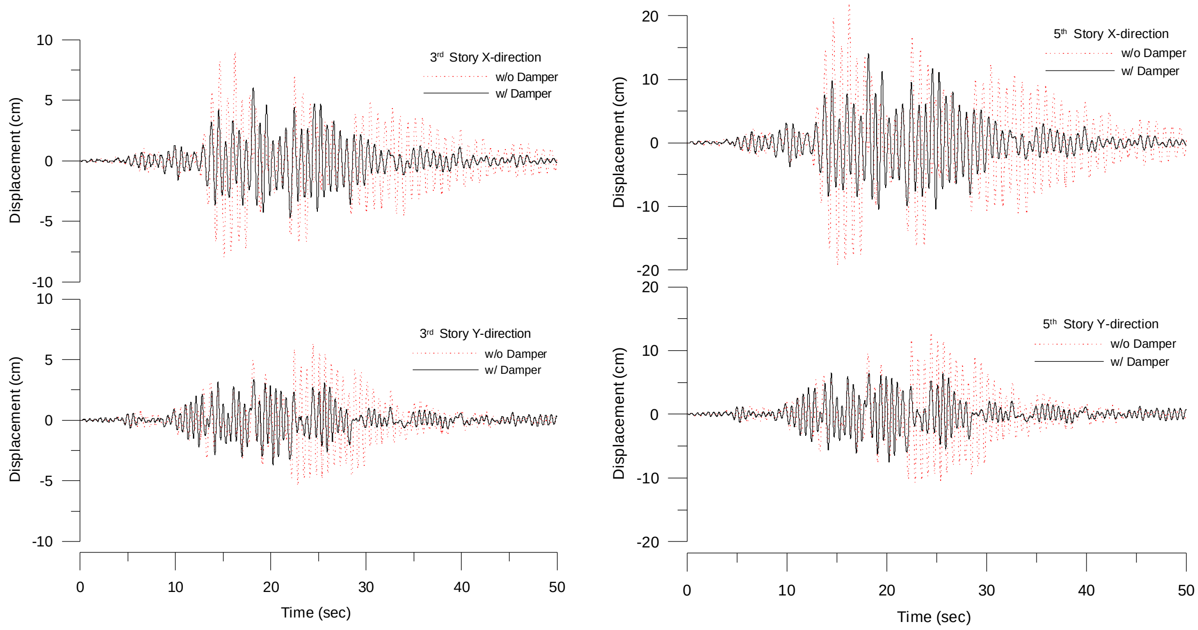

Figure 10(a) Comparison of displacement responses (3F & 5F)-PGA=0.50g

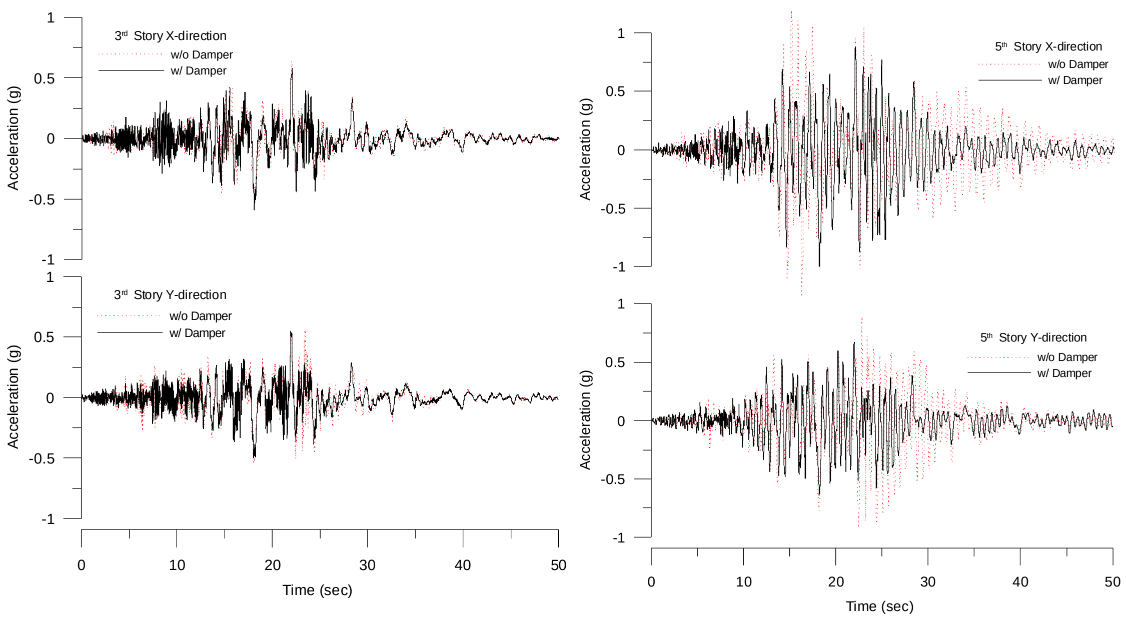

Figure 10(b) Comparison of acceleration responses (3F & 5F)-PGA=0.50g

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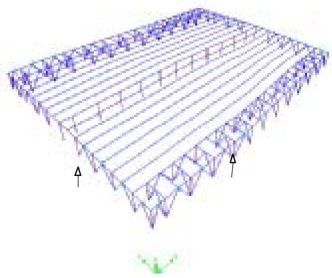

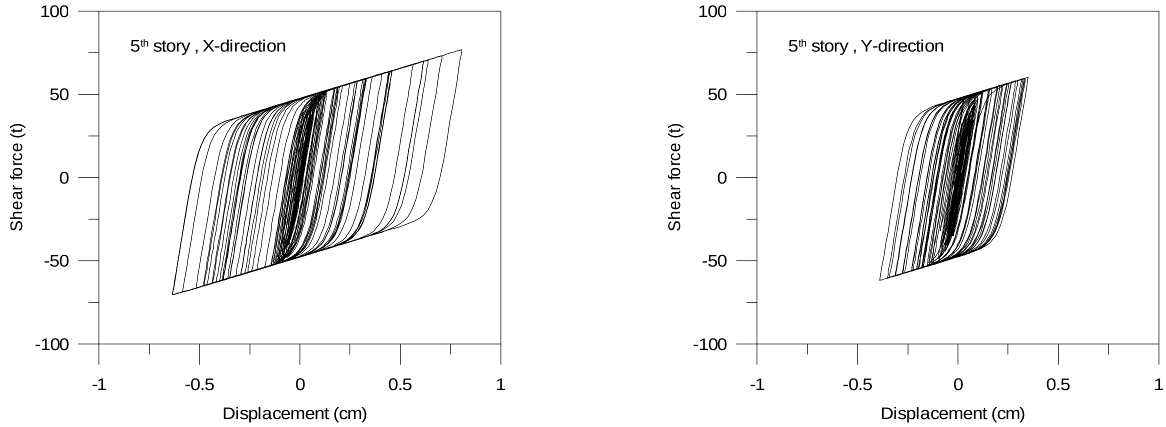

Figure 11(a) Hysteresis loops of the damper-PGA=0.33g

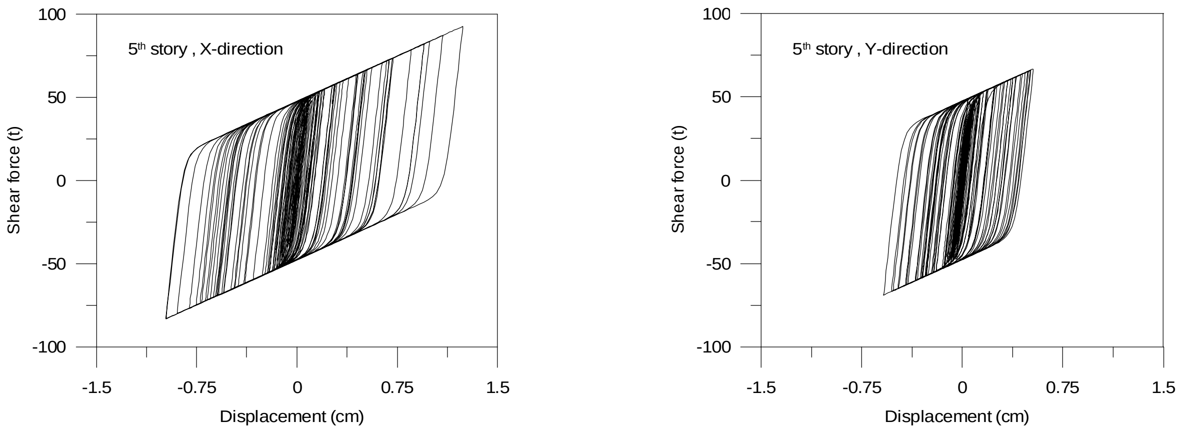

Figure 11(b) Hysteresis loops of the damper-PGA=0.50g

CONCLUSIONS

This study investigates the potential seismic risks of the double fab structures in Taiwan's semi-conductor industry and the feasibility of seismic retrofit by using metallic yielding dampers. In accordance with the simulation results, the conclusions are summarized below:

(1) Excessive storydrifts of the double fab are found between the clean room levels under the design earthquake intensity. The concern of the double fab structure containing soft and weak stories has been confirmed.

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(2) The soft and weak-story problem of the double fab can be greatly relieved by introducing metallic yielding dampers for seismic retrofit. The proposed seismic retrofit design proves to be effective and sufficient in enhancing the seismic performance of the double fab structure under the design earthquake intensity. It, however, has not been sufficient at the earthquake intensity level of PGA=0.5g, and more dampers are demanded for further improvement of the seismic performance.

(3) The code specified design values for seismic anchorage of facility are somewhat conservative as compared with the time history responses under the specific earthquake episode with PGA=0.33g considered. Nevertheless, this does not warrant damage-free and function integrity of the tools from a performance-based design point of view.

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