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THE EXPERIMENTAL STUDY OF THE CONSTRUCTION METHODS FOR STONE VENEERS IN TAIWAN

Fan-Ru Lin[1], George C. Yao[2], Shyh-Jiann Hwang[3], Chien-Chuang Tseng[4], Pu-Wen Weng[5]

ABSTRACT

Cooperating with a large experiment program for RC frame directed at NCREE, this study revised the performance based design objectives by cyclic loading tests for stone veneers with different construction methods in Taiwan. The configuration of interior and exterior veneers was arranged according to the thickness of originally designed RC walls. Different types of attachment devices for interior and exterior veneers were presented, and expected drift ratio values from different standards were tested in this experiment as well. Summarizing the results of tests, interior veneers attached by grouting with cement mortar showed the poorest seismic deformation capability when the drift ratio of RC frame achieved 0.5%. The exterior veneers fastened by mechanical anchors showed good seismic performance and only minor damage in out-of-plane deformation.

Introduction

Veneers of stone materials are popular building decoration elements for both exterior and interior decoration components in Taiwan, and usually placed at entrances and lobbies in public buildings or modern apartment complex to create elegant appearance. However, stone veneers with inappropriate construction methods may become falling hazards and obstructions along escape egress during and after strong earthquakes, and thus cause unexpected severe casualties. In 1999 Chi-Chi earthquake, dislodged exterior and interior adhered stone veneers could be found in hospitals and residential buildings (Fig. 1).

Figure 1. Stone veneer damages at Taiwan Central Area in Chi-Chi Earthquake.

[1 4 5]Associate Research Fellow, National Center for Research on Earthquake Engineering ,Taipei, Taiwan
[2]Professor, Dept. of Architecture, National Cheng Kung University ,Tainan, Taiwan
[3]Professor, Dept. of Civil Engineering, National Taiwan University ,Taipei, Taiwan

According to the investigation for damage modes of exterior stone veneers in Chi-Chi Earthquake (Guo and Chen, 2000), only one damaged anchored veneer case was observed caused by inadequate joints, and other 43 damaged cases were all adhered veneers. Most parts of adhered veneers were failed at the interfaces of adhesion layers, while the damage may happen at the interface between stone veneer and adhesion layer (55.4%), at the interface between the backup component and adhesion layer (37.8%), at backup component (4.1%), or at inadequate joints between veneers (2.7%). In the 43 investigated building cases, 34.9% adhered veneers had no additional mechanical means.

After Chi-Chi Earthquake, there are some changes in the construction methods for stone veneers. First, in order to avoid both stain problem and seismic hazards, exterior veneers are preferred to use anchored ones rather than adhered ones. Second, several new materials and construction methods are extensively used. As shown in the right photo of Fig. 2, undercut anchors are commonly used for thick anchored veneers besides traditional strap anchors (left two photos). In addition, polymerized tile gripper is used as adhesion materials for interior veneers besides mortar and seaweed paste.

Figure 2. Attachment device types of exterior stone veneers.

Specified Drift Ratio Values for Stone Veneers

Due to the large possibility of causing falling hazards, exterior and interior stone veneers are generally recommended to be rehabilitated in the high seismicity zone. In FEMA 356, stone veneers are required rehabilitated in all Nonstructural Performance Level objectives. According to the seismic response sensitivity, stone veneers are typically classified as deformation-sensitive components, and acceleration response is secondary concern. For deformation analysis of stone veneers, drift ratio values are often used as acceptance criteria. However, lacking of data about the relationship between damage states and drift ratio values, the limiting drift ratio values in guidelines and standards are suggested based on experiences and professionals' opinions. Therefore, the purpose of this study is to observe and record damage states of stone veneers with local construction methods in specified drift ratio values.

As shown in Table 1, damage states in specified drift ratio values of related performance levels are defined from several guidelines and standards. Drift ratio values of primary and secondary RC wall elements in FEMA 356 and SEAOC were also adopted in this test, since the performance of veneers should coincide with their backup components. In FEMA 356, the drift ratio for both exterior and interior adhered veneer in Life Safety nonstructural performance level shall be limited to 0.02, and in Immediate Occupancy nonstructural performance level shall be limited to 0.01.

Table 1. Specified drift ratio values for stone veneers and backup walls

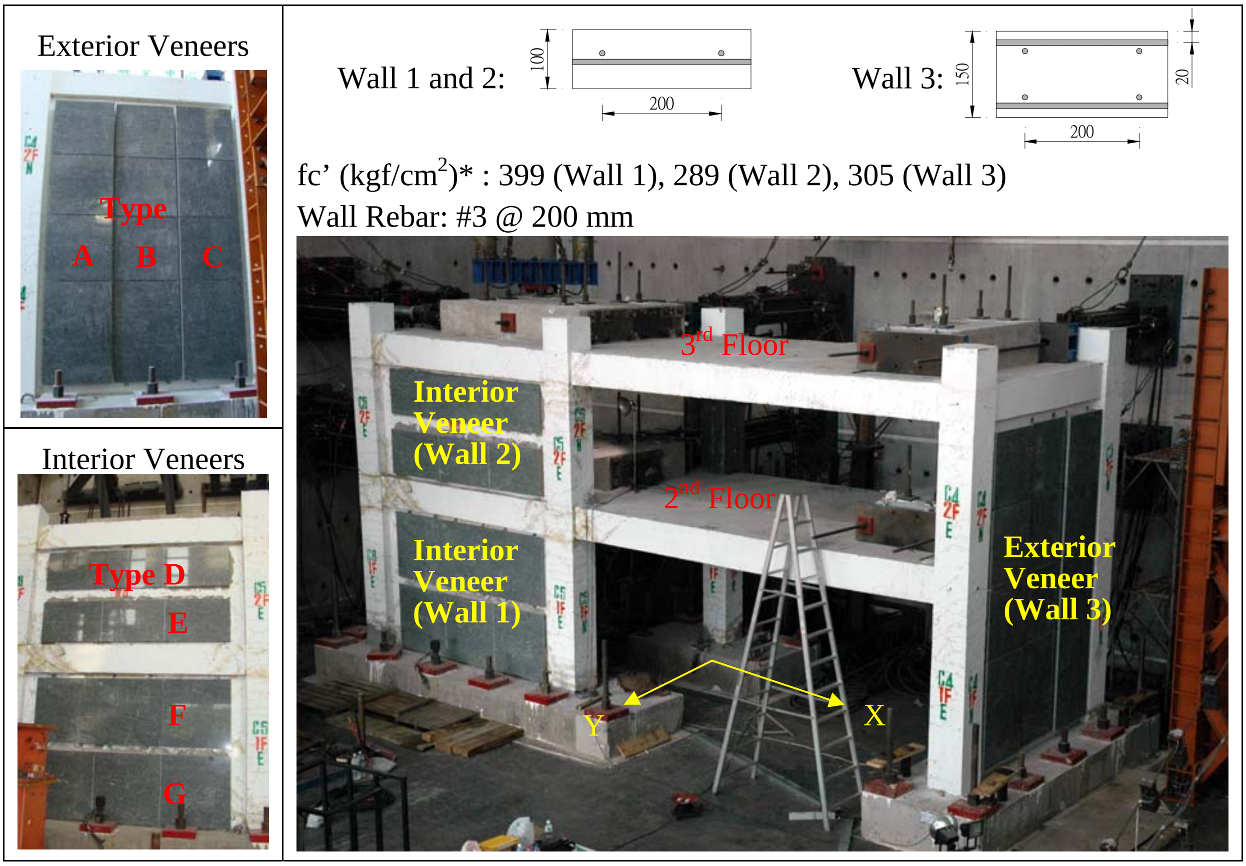
DR (%)*	Reference	Performance Level	Required Damage States		
0.2	SEAOC	Fully Operational	Cladding, primary and secondary concrete walls		Negligible
	JASS 9	-	Wet construction with prevention of crack may be used for low-rise buildings (10 m)		
0.33	JASS 9	-	Joints of anchored exterior veneers should accommodate drift ratio 1/300.		
0.5	SEAOC	Operational	cladding		Connections yield; some cracks or bending
			Concrete wall	primary	Minor hairline cracking (0.5mm) of walls
				secondary	Same as primary; sliding at construction joints
	FEMA 356	Immediate Occupancy	cladding		Connections yield; minor cracks (<1.6mm width) or bending in cladding.
			Concrete wall	primary	Minor hairline cracking of walls, <1.6mm wide.
				secondary	Minor hairline cracking of walls. Some evidence of sliding at construction joints. Minor spalling.
1.0 (0.5)**	FEMA 356	Life Safety	cladding		Severe distortion in connections. Distributed cracking, bending, crushing, and spalling of cladding elements. Some fracturing of cladding, but panels do not fall.
1.5	SEAOC		Concrete wall	primary	Some boundary elements distress including limited bar buckling; some sliding at joints; some crushing and flexural cracking; cracks; some crushing, but concrete generally remains in place.
				secondary	Major flexural and shear cracks; sliding at joints; extensive crushing; severe boundary element damage
2.0	FEMA 356	Hazards Reduced (Collapse Prevention)	cladding		Severe damage to connections and cladding; some falling of panels
			Concrete wall	primary	Major flexural and shear cracks and voids; sliding at joints; extensive crushing and buckling of rebar; sever boundary element damage
2.5	SEAOC			secondary	Panels shattered, virtually disintegrated
13 (mm)	ASCE 7-05	-	Connections and panel joints of exterior wall elements shall accommodate the minimum story drift 13 mm caused by seismic motion		

*: DRs in FEMA 356 are for concrete walls; DRs in other standards are for buildings.
**: Permanent drift ratio

Planning for Cyclic Loading Test

As discussed above, testing data on the damage states of veneers and drift ratio values is inadequate, and one of the reasons is that it requires enormous funds to construct a full size concrete wall to achieve the required drift ratio values. Through the opportunity from cooperative project between the National Center of Research for Earthquake Engineering and University of Houston, a two floor 3D-specimen with RC walls can be reused to execute a cyclic loading test for revising the acceptable criteria of the stone veneers installed in Taiwan. As shown in Fig. 3, actuators were installed at 2nd and 3rd floors and induced force into wall specimens through boundary elements. The configuration of three exterior veneer types (Type A~C) and four interior veneer types (Type D~G) was arranged according to the thickness of RC walls and construction experiences. For instance, tile gripper (Type D) is usually applied at upper area of interior walls, where cement mortar grout (Type E) is hard to implement due to the limited working space.

The fixing positions of anchored veneers are scheduled to avoid the wall rebars (Fig. 4). A common marble category, polished Grigio Carnico material was chosen for stone veneers. Installation of stone veneers was accomplished by a medium-scale contractor specialized in stone works. As shown in Fig. 5, Fig. 6 and Table 2, specifications and drawings for attachment devices of exterior and interior veneers were decided according to local construction experiences.



*: Concrete cylinder testing data was referred to Lee and Hwang (2009).

Figure 3. Configuration of Veneers in the 3D-specimen with RC walls

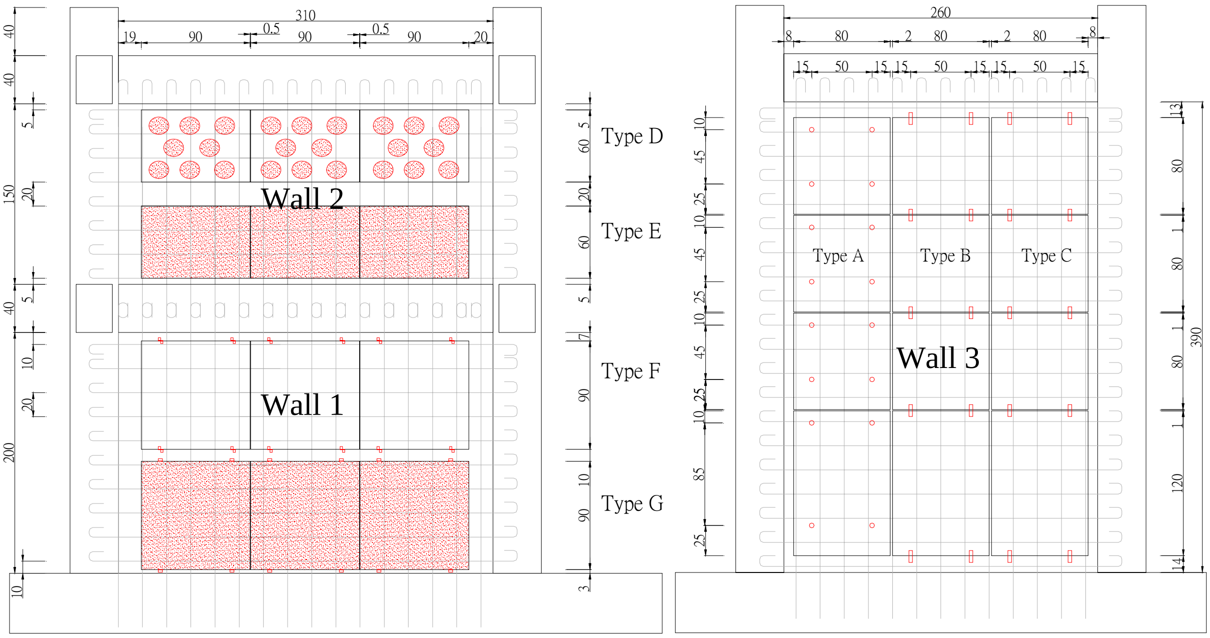
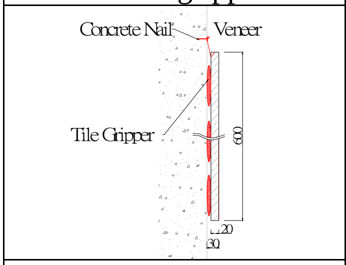
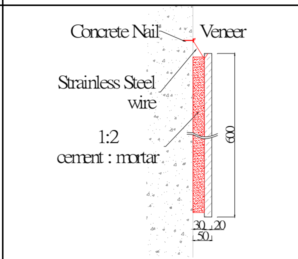
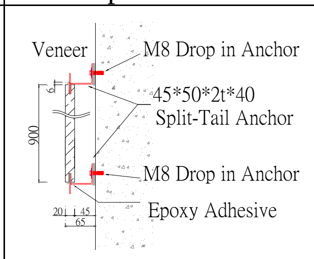
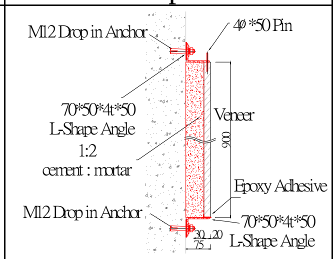


Figure 4. Layout of Exterior and Interior Veneers (unit: cm)

Type D. Partial adhered with tile gripper*	Type E. Grouting with cement mortar*	Type F. Anchored with Split-tail anchor	Type G. Grouting and with strap anchor
			
			

*: Surfaces of Wall 1 and Wall 2 had been roughed before construction although paint affects adhered strength slightly (Guo and Chen, 2000).

Figure 5. Details of Interior Veneers (unit: mm)

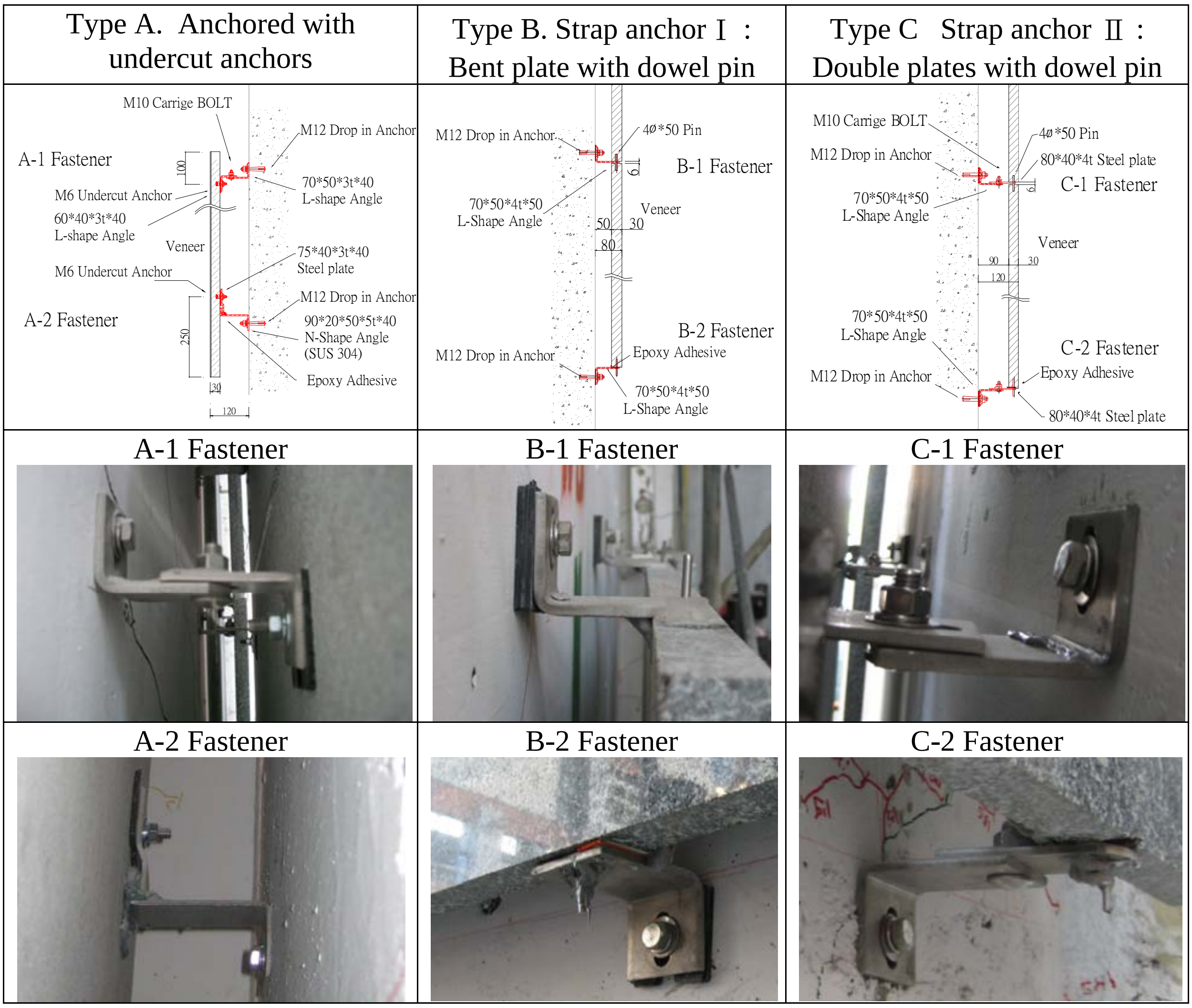


Figure 6. Details of Exterior Veneers (unit: mm)

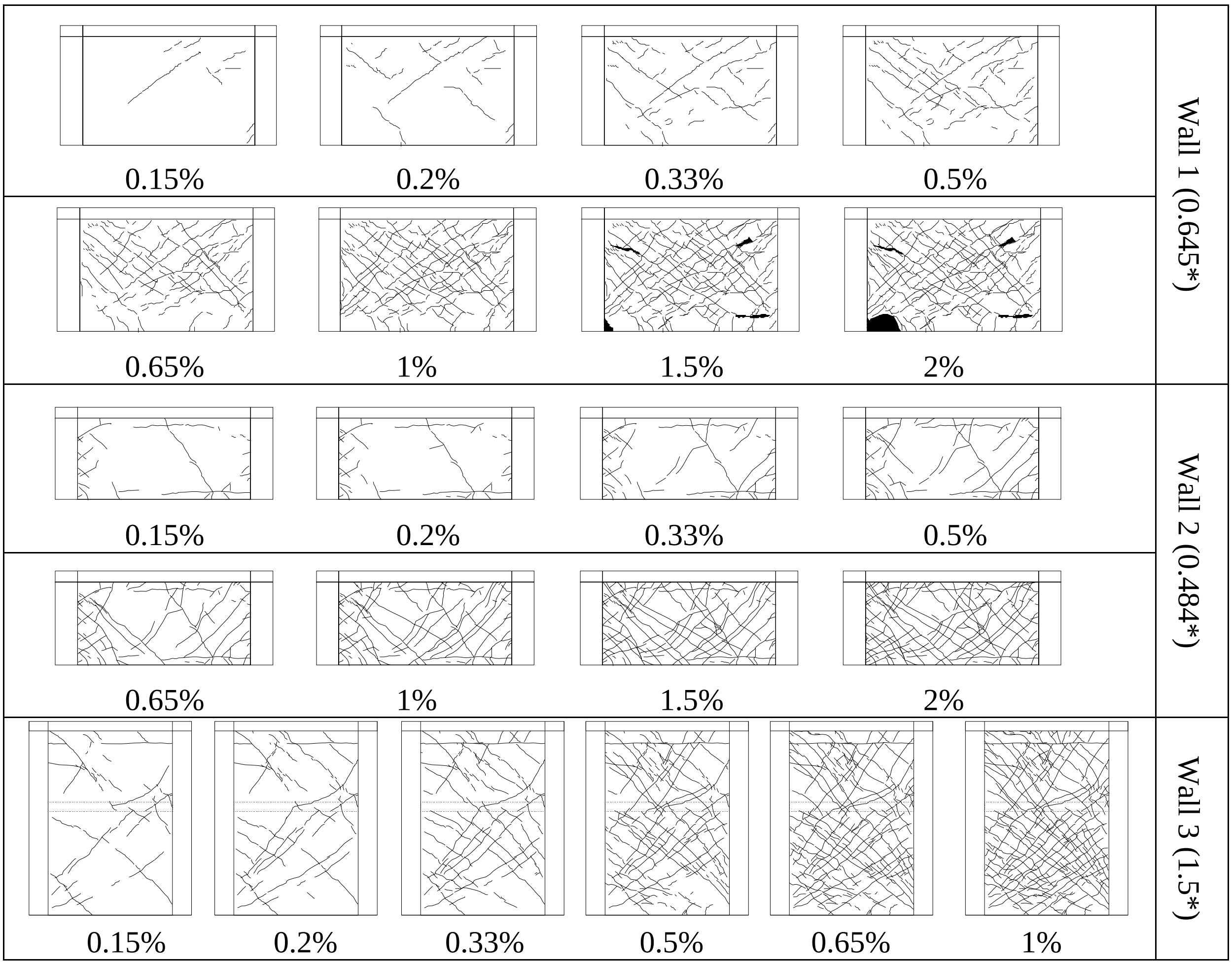
Table 2. Details of Attachment Devices

Type	**Attachment Devices**		
	to Veneer	**Interface**	**to Wall**
A	Undercut anchor (M6) (anchorage depth 13mm)	Angles & plates	Drop-in Anchor (M12) (anchorage depth 40mm)
B	Pins & Epoxy Adhesive	Angles	
C		Angles & plates	
D	Polymerized Tile Gripper (tensile strength 17.6kgf/cm^2)*/ Concrete Nail & Steel Wire		
E	Cement Mortar (1:2) / Concrete Nail & Steel Wire (φ 0.5mm)		
F	Split-Tail Anchor & Epoxy Adhesive	Split-Tail Anchor	Drop-in Anchor (M8) (anchorage depth 30mm)
G	Pins & Epoxy Adhesive	Angles & cement mortar (1:2)	Drop-in Anchor (M12) (anchorage depth 40mm)

*: Tensile strength was offered by the manufacturer Nan Shing Colour Company.

Cyclic Loading Test Results and Applications

According to acceptable criteria in guidelines and standards, expected drift ratio values of cyclic loadings were decided in Table 3. Cyclic loading in X or Y direction were executed by turns, and each drift ratio was repeated 3 times to ensure the required drift ratio was achieved. The 2nd and 3rd floors were forced to the same drift ratio in X direction to give all interior veneer types the same deformation requirement. Two groups of maximum drift ratio values in each loading was shown in Table 3, which were measured from actuators connected to floors and from displacement transducers connected to wall specimens at diagonal points. Comparing achieved and expected drift ratio values, most drift ratio values of floors could conform to expected ones. However, drift ratios of wall specimens were much smaller due to the deformation of walls and the whole frame while expected drift ratio values were small than 1.0%, but they conformed while drift ratio exceeded 1.0 % in X direction while primary cracks ran through wall specimens (Fig. 7). Several cracks of three Wall Specimens exceeded 1.5mm when expected drift ratio is 1.0%, and partial area of concrete crushed and fell in Wall 1 when expected drift ratio is 2.0%.



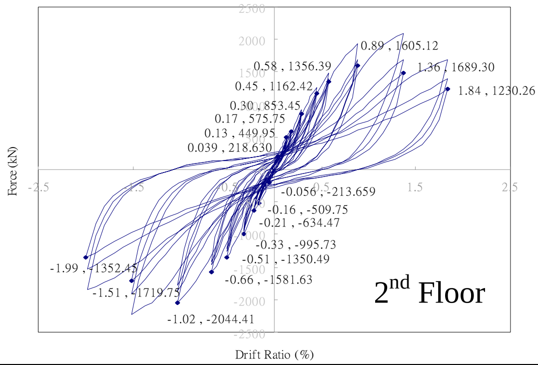
*: height-to-width ratio

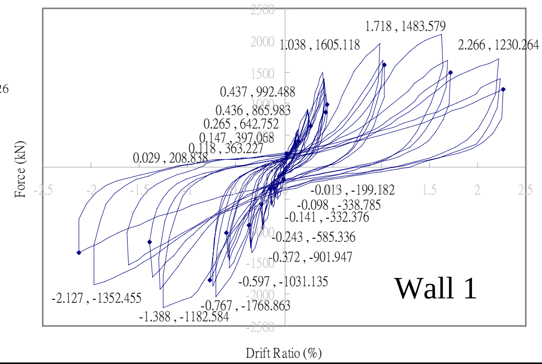
Figure 7. Crack in Wall Specimens

Table 3. Achieved Drift Ratio (DR) of Wall Specimens

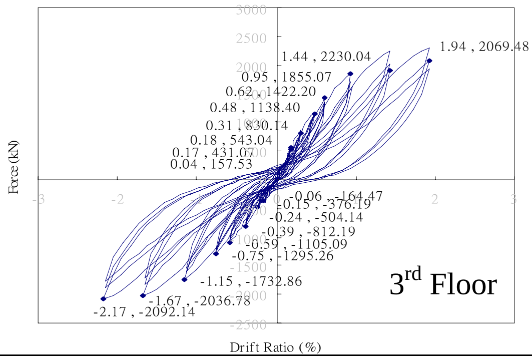
Expected DR (%)	Achieved DR (+: push -: pull)					
	Wall 1 (%)		Wall 2 (%)		Wall 3 (%)	
	2nd Floor	Wall 1	3rd Floor	Wall 2	3rd Floor	Wall 3
0.05	0.056 (-)	0.029 (+)	0.064 (-)	- *	0.058 (-)	0.031 (+)
0.15	0.156 (-)	0.118 (+)	0.170 (+)	0.084 (+)	0.160 (-)	0.079 (-)
0.2	0.209 (-)	0.147 (+)	0.238 (-)	0.103 (+)	0.213 (-)	0.104 (+)
0.33	0.332 (-)	0.265 (+)	0.392 (-)	0.249 (+)	0.340 (-)	0.204 (+)
0.5	0.506 (-)	0.436 (+)	0.585 (-)	0.432 (+)	0.520 (-)	0.323 (+)
0.65	0.659 (-)	0.597 (-)	0.749 (-)	0.582 (+)	0.667 (-)	0.407 (+)
1	1.018 (-)	1.038 (+)	1.147 (-)	0.924 (+)	0.958 (-)	0.685 (+)
1.5	1.505 (-)	1.718 (+)	1.672 (-)	1.486 (+)	- **	- **
2	1.987 (-)	2.266 (+)	2.173 (-)	2.021 (+)	- **	- **

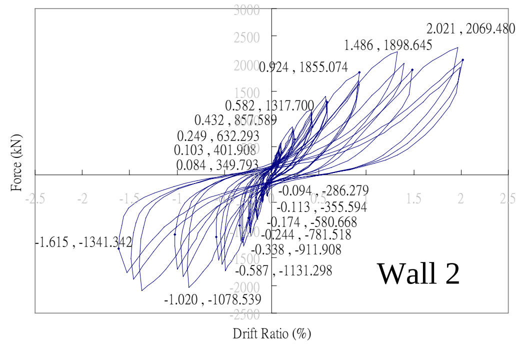
Wall 1 (X Dir.)



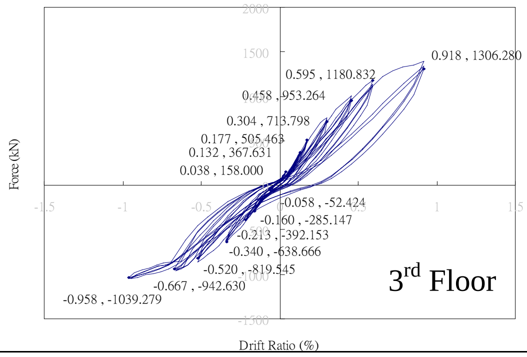


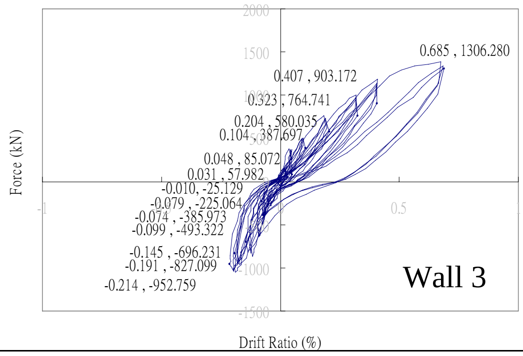
Wall 2 (X Dir.)





Wall 3 (Y Dir.)





*: Mistakes happened in the Displacement Transducer.

**: Required forces were over the limit of actuators in Y-direction.

As shown in Fig. 8 to Fig. 10, damage states of veneers were classified to several performance levels according to FEMA 356 and test results. In this test, Nonstructural Performance Level was expected to be the same as the Structural Performance Level. As the result of tests, three exterior veneer types had high capacity, except the epoxy may split when drift ratio achieved 1.0% (0.685% of Wall 3). In addition, opening was obviously observed when drift ratio achieved 2.0% in out-of-plane axis. Considering poor capacity of adhered veneers, each type of interior veneers was arranged in a single row to avoid weight transfer effect. However, two types of interior veneers still failed during this test (Fig. 9). Type-E and Type-D separated from backup wall and were hung by stainless steel wires when expected drift ratio were 0.5% and 0.65% (0.432% and 0.582% of Wall 2), and fell when expected drift ratio was 1.0% (0.924% of Wall 2). In addition, two anchored interior veneers still remained in place although Type G devices had severe distortion while expected drift ratio was 2.0% (Fig. 10).

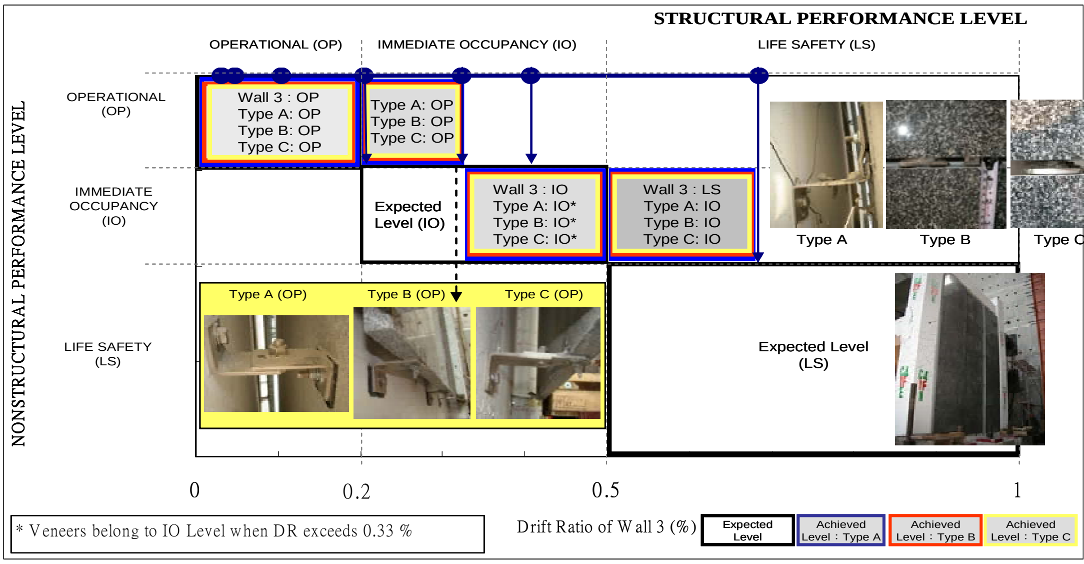


Figure 8. Achieved Performance Level of Exterior Veneers (Type A~C)

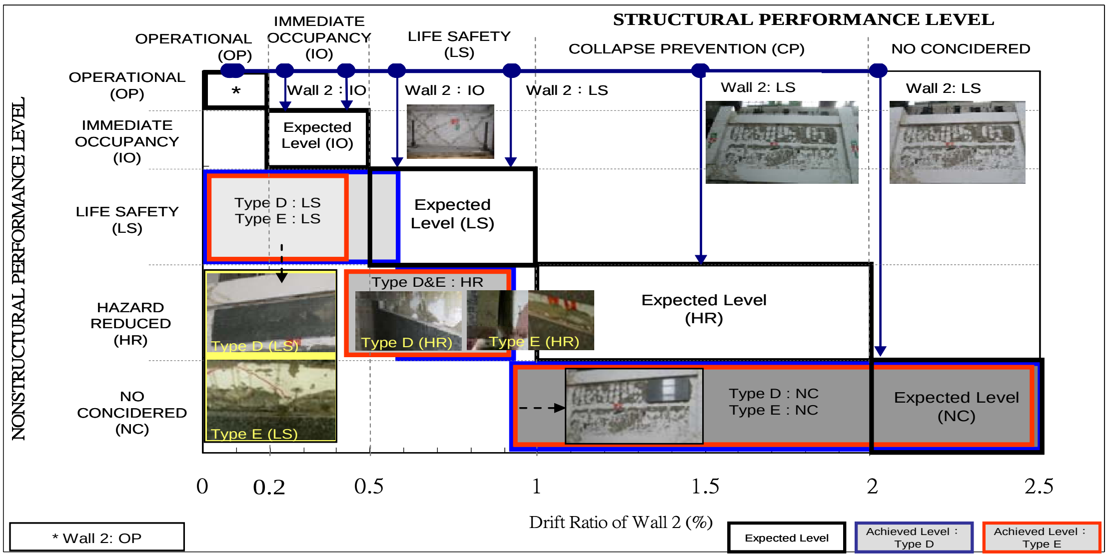


Figure 9. Achieved Performance Level of Interior Veneers (Type D~E)

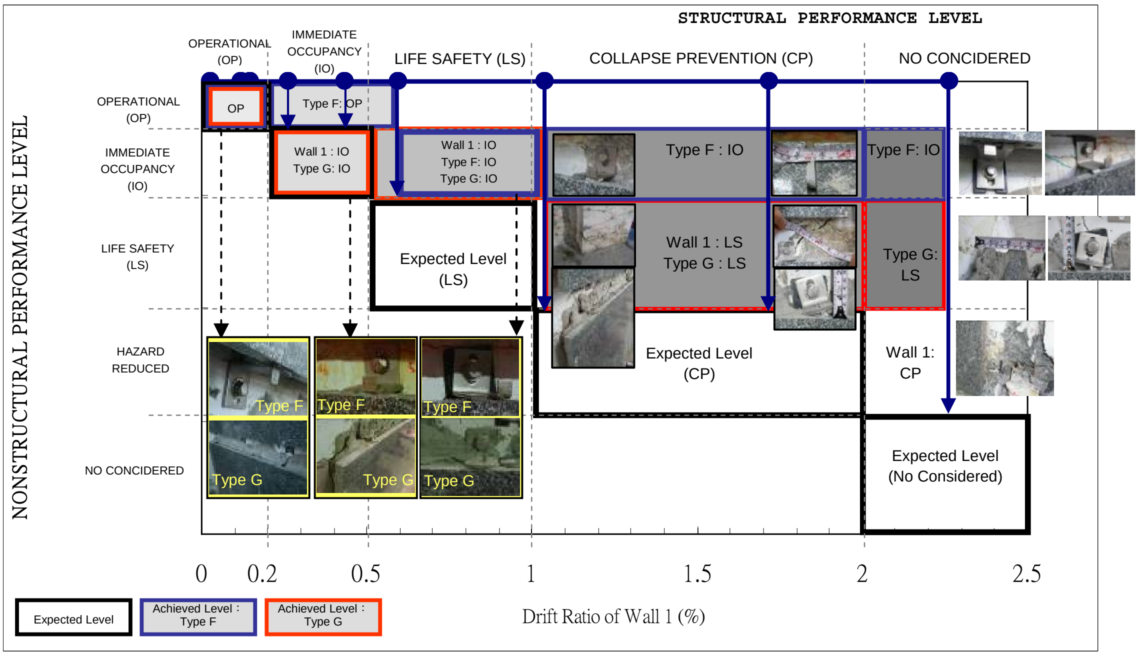


Figure 10. Achieved Performance Level of Interior Veneers (Type F~G)

Conclusions

In this study, different types of attachment devices for interior and exterior veneers in Taiwan were presented. Damage states under several specified drift ratio values were observed to verify their performance levels. As a result, anchored exterior and interior veneers conformed, even exceeded, their expected nonstructural performance levels. However, two adhered interior veneer types, attached by polymerized tile gripper or grouted with cement mortar, couldn't reach expected nonstructural performance levels. In view of the secondary device of adhered veneers--stainless steel wires--isn't strong enough, it is recommended that adhered veneers are only considered conformable to Life Safety Performance Level when drift ratio of the attached wall is lower than 0.2 %.

References

Y. X. Guo, and Tai-nung Chen, 2000. The research on the adhesive strength of wet construction for the stone on the building wall, *M.D. Thesis*, National Cheng-Kung University, Tainan, Taiwan.

H. T. Wu, and Tai-nung Chen, 2004. The research on the application of dry construction for stone fastener-supported anchors on the external wall, *M.D. Thesis*, National Cheng-Kung University, Tainan, Taiwan.

Yi-Tsung Lee, and Shyh-Jiann Hwang, 2009. Experiment of RC Building Frame Containing Walls Subjected to Bi-directional Cyclic Loading, , *M.D. Thesis*, National Taiwan University, Taiwan.

FEMA, 2000, *Prestandard and Commentary for the Seismic Rehabilitation of Buildings*, FEMA 356, Washington DC.

SEAOC, 1996, *Recommended Lateral Force Requirements and Commentary*, California.

ASCE, 2005, *Minimum Design Loads for Buildings and Other Structures*, SEI/ASCE 7-05, American Society of Civil Engineers, Reston, VA.

Architectural Institute of Japan, 1987, *Japanese Architectural Standard Specification JASS 9 Stone Work* (in Japanese), Japan.