Citation: Ramos, W., S. Sugano (2020), Evaluation and retrofitting of a historic adobe masonry building, Synopsis of IISEE-GRIPS master report.

EVALUATION AND RETROFITTING OF A HISTORIC ADOBE MASONRY BUILDING

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ABSTRACT

Most historic buildings in El Salvador are made out of adobe, a type of earth masonry that is non-engineered and extremely weak against earthquakes. This study was conducted to find the best solution for the retrofitting of these buildings. A 150-years-old adobe building was evaluated considering three retrofitting solutions: Polypropylene band wrapping, Backside wall affixing, and RC frame affixing. The analysis was conducted using three methods (JBDPA Guidelines, capacity spectrum method, and response history analysis), and two levels of seismic demand. The Polypropylene band wrapping solution was not enough for a building this weak and a site with such seismicity. The RC frame affixing solution worked, but it requires partial demolition works and causes extensive cracking on the walls. Finally, the Backside wall affixing technique presented a failure mode that protects the walls from damage while avoiding an aggressive alteration of the building in the low seismic demand level.

Keywords: Adobe, Retrofitting, Historic building, PP-band, Backside Wall.

1. INTRODUCTION

Adobe buildings have an innately low seismic capacity, which makes them unattractive as legitimate dwellings. However, even though public opinions on adobe buildings are generally negative, those buildings can't be demolished because El Salvador's Cultural Heritage law protects them. Therefore, the only option left is to retrofit them. Even though retrofitting is necessary to bring a building to an acceptable seismic performance level, the works allowed by the Ministry of Culture are severely limited because most of the techniques preferred by contractors are aggressive and affect the cultural value of the buildings. There is a real need to find the most appropriate retrofitting techniques that can increase the seismic performance of existing adobe buildings without compromising their historical value. Therefore, the objectives of this study are: 1) To apply the results of Salvadorian adobe masonry research, building codes, and Japanese evaluation, analysis, and retrofitting practices into the study of a real historic building; 2) To determine the most appropriate retrofitting technique for a historic adobe masonry building, to increase its seismic performance, without compromising its historic value.

2. DATA FROM THE TARGET BUILDING

The target building is a 150 years old adobe structure located in the city of Izalco, in western El Salvador. It has only one story, with a size of 31 m x 30 m, and it is C shaped (Fig. 1). All of the walls have a structural thickness of 75 cm (without plaster), a height of 3.80 m, and lack any reinforcement. The roof has a two-way shape and contains clay tiles resting on a timber structure. The structural analysis of the target building was conducted using Taiki Saito's Stera3D. A simple model was evaluated in both the N-S direction and the E-W direction, considering only in-plane responses in the walls. Therefore, the retrofitting techniques chosen for this study were those that could increase the in-plane capacity of the walls., the retrofitting techniques were designed to limit the eccentricity of the building to a minimum to mitigate any possible torsional effects caused by the irregularity of the building. The results of the

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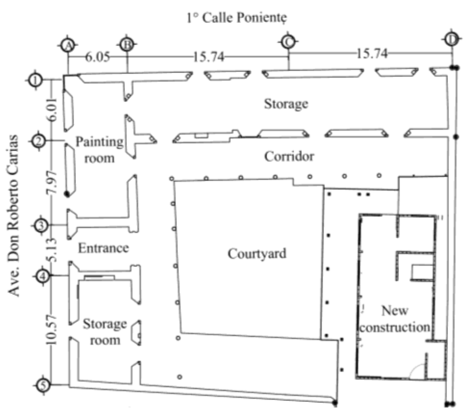

Figure 1. Architectural plan of the building.

TAISHIN Project, conducted by the universities UCA and UES, were used to model the structural behavior of the adobe walls. Material and-full scale test results from the first and second phase of the TAISHIN Project were taken, obtaining four idealized curves, for which the lower envelope was chosen as the model skeleton curve for unreinforced adobe masonry. This model had the maximum drift value of the adobe walls equal to 1/2000. The skeleton curve of every wall in the target building was calculated using this model, and the seismic index of the original building was calculated, obtaining that the Is values (Table 1) were lower than those required by the JBDPA standards. Thus, the building needs retrofitting.

Table 1. Seismic Index of the target building.

Direction	Story	1st level		2nd level		Result
		Is	Iso	Is	Iso	
N-S	1	0.12	0.80	0.14	0.60	FAIL
E-W	1	0.12	0.80	0.17	0.60	FAIL

3. METHODOLOGY

The first step in determining whether a retrofitting technique is successful or not is to set the analysis methods to be used in the analysis, followed by the seismic demand, and finally, by setting the criteria for a successful retrofitting. The seismic capacity of the retrofitted building was set to be calculated using three methods: 1) Capacity Spectrum method, where a pushover analysis was conducted on the retrofitted model in Stera3D and compared to the spectrum determined by the demand level; 2) JBDPA Guidelines, where the strength factor (C) and the ductility factor (F) were to be determined by the structural retrofitting model and compared to the Iso values determined by the demand level; and 3) Response History Analysis, where the demand spectrum would be utilized to generate two waveforms using both a crustal earthquake (1995 Kobe eq.) and a subduction earthquake (2001 El Salvador eq.) as envelope functions. The next step is to determine the seismic demand level (Fig. 2).

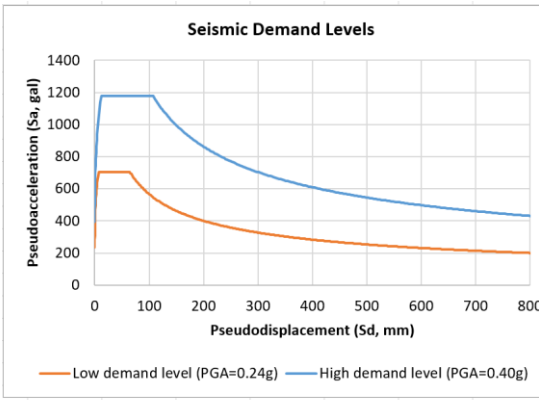

Figure 2. High vs low demand spectra.

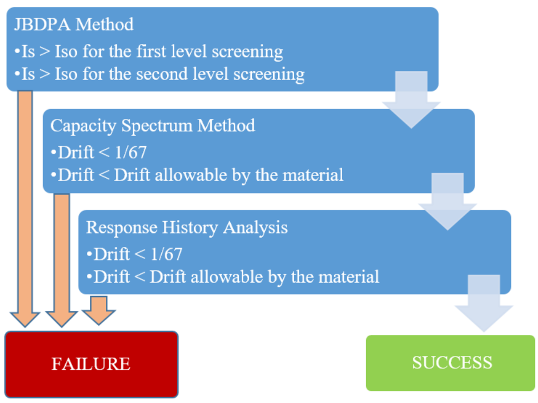

Figure 3. Criteria for a successful retrofitting.

The demand level depends on whether or not reducing the impact of the retrofitting is more crucial than ensuring its habitability. For this study, two levels were considered: 1) The high demand level is designed to ensure that the building withstands all the strong motions that could appear in its lifetime, making it fit for human habitation, but resulting in a more expensive and aggressive retrofitting. This demand level is obtained according to the Salvadorian Seismic Code, consisting of a design spectrum with a PGA based on the country's seismic zoning. The building is located in the Seismic Zone I. For a ground motion with a probability of exceedance of 10% in 50 years, PGA is equal to 0.4g. 1) The low demand level is designed to ensure that the retrofitting works are more respectful of the historic value of the building, but this results in a design that doesn't ensure habitability because there is a risk that a strong motion can cause the collapse of the building during its lifetime. For buildings whose historic value is more important than its habitability, this demand level can be used. The reduced demand was estimated using a Probabilistic Seismic Hazard Analysis (PSHA) of earthquakes in the region, and the ground motion with a probability of exceedance of 50% in 50 years was obtained (PGA=0.24g). As for the retrofitting strategy, the following process was adopted: 1) Improvement of irregularity by adding a south wall; 2) Stiffening of the roof level of the walls by adding an RC head beam anchored to the adobe walls; 3) Retrofitting of the walls using three retrofitting techniques and comparing them: --Polypropylene band wrapping (Fig. 4): Plastic bands are wrapped in a mesh around the walls and tied to the head beam and foundation. The retrofitted building is expected to show a significant increase in ductility. --Backside wall affixing (Fig. 5): RC wall built next to the adobe wall, tied to the head beam and foundation. The retrofitted building is expected to show a significant increase in strength. --RC frame affixing (Fig. 6): RC frame embedded in the adobe wall, encased in a clay brick casing. The retrofitted building is expected to show a considerable increase in ductility and strength, making it a mixed technique. All retrofitting techniques were evaluated according to the procedure shown in Fig. 3.

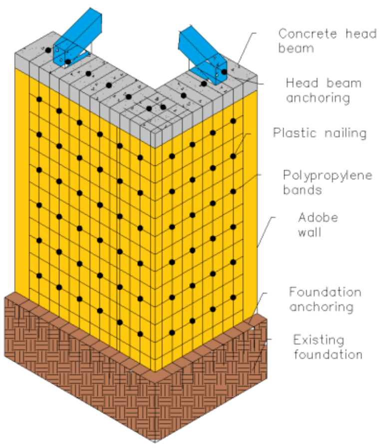

Figure 4. PP-band wrapping.

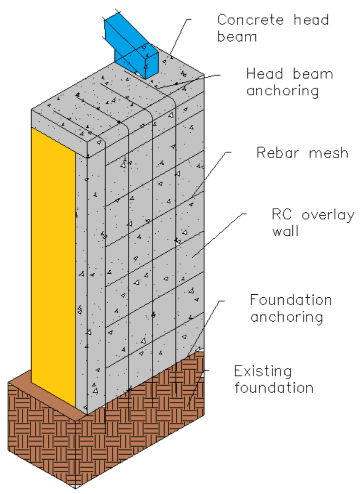

Figure 5. Backside wall.

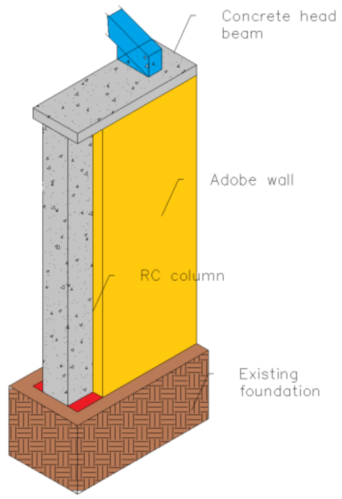

Figure 6. RC Frame affixing.

4. RESULTS AND DISCUSSION

Polypropylene band wrapping technique: Due to the lack of experimental data, a literature search on the structural behavior of polypropylene band wrapped masonry buildings subjected to in-plane motions was conducted. Three different research papers were selected: 1) Zhou et al., 2) Zohreh et al., 3) Mayorca & Meguro. To obtain the retrofitting model, first, the skeleton curves in all of the specimens were normalized to compare them to those of the non-retrofitted adobe building. Afterward, the retrofitted adobe skeleton curve was inferred by observing the changes in each of the reference studies and replicating the same changes in the original adobe skeleton curve. Out of the three results, the lower envelope was chosen as the model skeleton curve. This model had the maximum drift value of the retrofitted adobe walls equal to 1/215. This model was first evaluated using the capacity spectrum method. The capacity curve never reached the demand line, except for the E-W direction in the low demand level. After this, the JBDPA method was employed to determine the seismic capacity of the retrofitted building. The seismic indexes (Is) only reached values higher than the seismic demand indexes (Iso) for the E-W direction, low demand level, and only in the second level screening. Finally, the response history analysis was conducted, in which the only favorable results obtained were in the E-W direction, low demand level. The results are summarized in Tables 2 and 3.

Table 2. Results of the Polypropylene band wrapping technique, N-S direction.

North-South Direction							
	Analysis Method		Is		Iso		Result
			1st level	2nd level	1st level	2nd level	
High Demand	JBDPA Method		0.23	0.29	0.80	0.60	FAIL
	Analysis Method		Base shear	Drift	Max. Drift		Result
	Capacity Spectrum		-	-	1/215		FAIL
	Response History	1995 Kobe	0.294	1/47	1/215		FAIL
		2001 E.S.	0.339	1/71	1/215		FAIL
	Irregularity		11.20%				
	Analysis Method		Is		Iso		Result
			1st level	2nd level	1st level	2nd level	
Low Demand	JBDPA Method		0.23	0.29	0.48	0.36	FAIL
	Analysis Method		Base shear	Drift	Max. Drift		Result
	Capacity Spectrum		-	-	1/215		FAIL
	Response History	1995 Kobe	0.271	1/189	1/215		FAIL
		2001 E.S.	0.262	1/212	1/215		FAIL
	Irregularity		11.20%				

Table 3. Results of the Polypropylene band wrapping technique, E-W direction.

East-West Direction							
	Analysis Method		Is		Iso		Result
			1st level	2nd level	1st level	2nd level	
High Demand	JBDPA Method		0.35	0.43	0.80	0.60	FAIL
	Analysis Method		Base shear	Drift	Max. Drift		Result
	Capacity Spectrum		-	-	1/215		FAIL
	Response History	1995 Kobe	0.437	1/141	1/215		FAIL
		2001 E.S.	0.416	1/141	1/215		FAIL
	Irregularity		3.57%				
	Analysis Method		Is		Iso		Result
			1st level	2nd level	1st level	2nd level	
Low Demand	JBDPA Method		0.35	0.43	0.48	0.36	FAIL
	Analysis Method		Base shear	Drift	Max. Drift		Result
	Capacity Spectrum		0.412	1/1583	1/215		PASS
	Response History	1995 Kobe	0.298	1/538	1/215		PASS
		2001 E.S.	0.331	1/387	1/215		PASS
	Irregularity		3.57%				

<u>Backside wall affixing technique:</u> The first step in developing the backside wall affixing model was to find the skeleton curve of each adobe wall and each RC overlay. The skeleton curves of the adobe walls were identical to those obtained for the Polypropylene band wrapped walls because this method requires the wrapping of the walls before applying the overlay walls. For the estimation of the skeleton curves of the RC overlays, the method recommended by the AIJ guidelines was used. Then, the combined skeleton curve was equal to the skeleton curve of the adobe wall plus the overlays. This model had the maximum drift value of the retrofitted adobe walls equal to 1/250, therefore ensuring that the adobe walls don't fail before the overlays do.

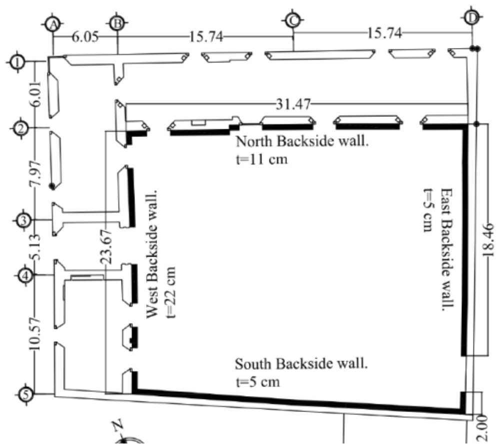

Figure 7. Backside walls, high demand level.

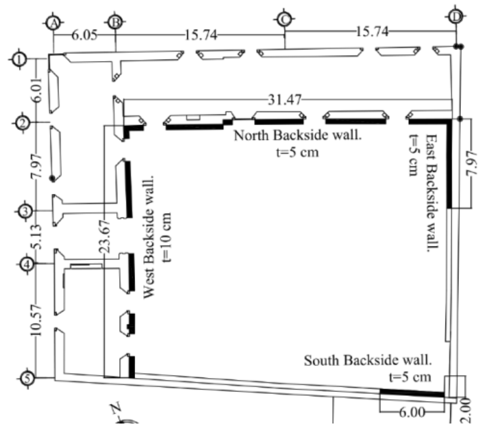

Figure 8. Backside walls, low demand level.

Afterward, the distribution of overlay walls (Figs. 7 and 8), dimensions, and reinforcement for both demand levels was chosen. The location of the walls was chosen to counteract the irregularity of the building, keeping the eccentricity levels under 5%. This model was first evaluated using the capacity spectrum method. The capacity curve reached the demand spectrum in both directions and both demand levels. After this, the JBDPA method was employed to determine the seismic capacity of the retrofitted building. The seismic indexes (Is) reached values higher than the seismic demand indexes (Iso) for both directions, both demand levels, and both 1st and 2nd level screenings. Finally, the response history analysis was conducted, in which all of the results obtained, in all levels and directions were less than the maximum allowable by the material (1/250). The results are summarized in Tables 4 and 5.

Table 4. Results of the Backside wall affixing technique, N-S direction.

	Analysis Method		North-South Direction				Result
			Is		Iso		
			1st level	2nd level	1st level	2nd level	
High Demand	JBDPA Method		0.81	0.86	0.80	0.60	PASS
	Analysis Method		B. Shear	Drift	Max. Drift		Result
	Capacity Spectrum		0.553	1/572	1/250		PASS
	Response History	1995 Kobe	0.472	1/529	1/250		PASS
		2001 E.S.	0.533	1/482	1/250		PASS
	Irregularity		4.52%				
Low Demand	Analysis Method		Is		Iso		Result
			1st level	2nd level	1st level	2nd level	
	JBDPA Method		0.50	0.50	0.48	0.36	PASS
	Analysis Method		B. Shear	Drift	Max. Drift		Result
	Capacity Spectrum		0.382	1/693	1/250		PASS
	Response History	1995 Kobe	0.334	1/1550	1/250		PASS
		2001 E.S.	0.386	1/975	1/250		PASS
	Irregularity		1.47%				

Table 5. Results of the Backside wall affixing technique, E-W direction.

	Analysis Method		East-West Direction				Result
			Is		Iso		
			1st level	2nd level	1st level	2nd level	
High Demand	JBDPA Method		0.93	1.00	0.80	0.60	PASS
	Analysis Method		B. Shear	Drift	Max. Drift		Result
	Capacity Spectrum		0.597	1/1145	1/250		PASS
	Response History	1995 Kobe	0.494	1/1214	1/250		PASS
		2001 E.S.	0.557	1/1494	1/250		PASS
	Irregularity		3.94%				
Low Demand	Analysis Method		Is		Iso		Result
			1st level	2nd level	1st level	2nd level	
	JBDPA Method		0.56	0.64	0.48	0.36	PASS
	Analysis Method		B. Shear	Drift	Max. Drift		Result
	Capacity Spectrum		0.437	1/1652	1/250		PASS
	Response History	1995 Kobe	0.372	1/2390	1/250		PASS
		2001 E.S.	0.377	1/3030	1/250		PASS
	Irregularity		3.62%				

RC frame affixing technique: The first step in developing the RC frame affixing model was to find the capacity curve of the adobe walls and the RC frames. The capacity curve of the adobe building was identical to that obtained for the Polypropylene band wrapped walls because this method requires the wrapping of the walls after constructing the embedded frames. The capacity curve of the RC frame was calculated directly using Stera3D. Then, the combined capacity curve was equal to the capacity curve of the adobe building plus that of the RC frame. This model had the maximum drift value of the retrofitted adobe walls higher than 1/67, which is the maximum drift allowable by the Salvadorian Seismic Code for regular buildings with fragile non-structural elements (1.5%). Thus the adobe walls suffer damage before the overall building collapses.

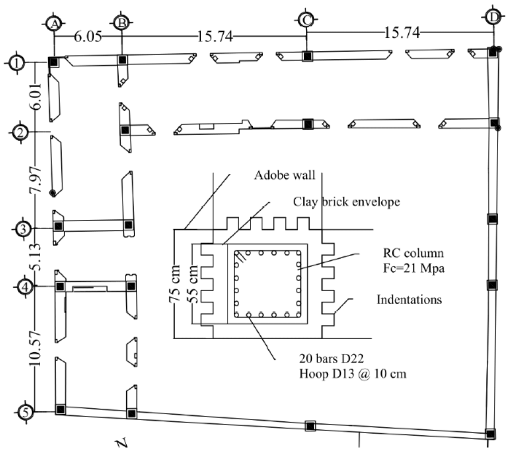

Figure 9. RC frame, high demand level.

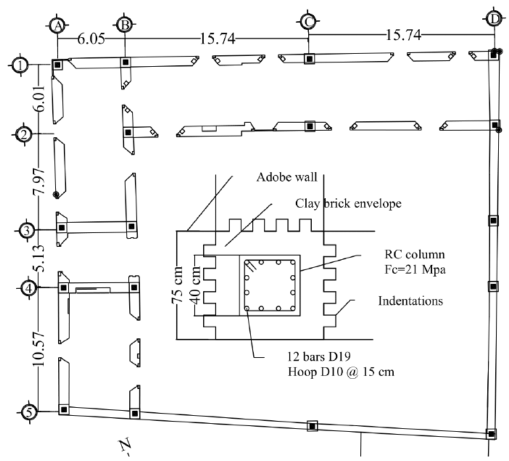

Figure 10. RC frame, low demand level.

Afterward, the distribution of the beams and columns (Figs. 9 and 10), dimensions, and reinforcement for both demand levels were chosen. The structure was designed to counteract the irregularity of the building, keeping the eccentricity levels under 5%. The beams were designed to carry vertical loads after the adobe walls lose its vertical carrying capacity (at a drift of 1/215). This model was first evaluated using the capacity spectrum method. The capacity curve reached the demand spectrum in both directions and both demand levels. After this, the JBDPA method was employed to determine the seismic capacity of the retrofitted building. The seismic indexes (Is) reached values higher than the seismic demand indexes (Iso) for both directions, both demand levels, and both 1st and 2nd level screenings. Finally, the response history analysis was conducted, in which all of the results obtained, in all levels and directions were less than the maximum allowable by the material (1/67). The results are summarized in Tables 6 and 7.

Table 6. Results of the RC frame affixing technique, N-S direction.

			North-South Direction				
	Analysis Method		Is		Iso		Result
			1st level	2nd level	1st level	2nd level	
High Demand	JBDPA Method		0.82	0.76	0.80	0.60	PASS
	Analysis Method		B. Shear	Drift	Max. Drift		Result
	Capacity Spectrum		0.910	1/147	1/67		PASS
	Response History	1995 Kobe	0.579	1/406	1/67		PASS
		2001 E.S.	0.822	1/73	1/67		PASS
	Irregularity	Comb.	2.21%				
		RC Only	1.10%				
Low Demand	Analysis Method		Is		Iso		Result
			1st level	2nd level	1st level	2nd level	
	JBDPA Method		0.49	0.36	0.48	0.36	PASS
	Analysis Method		B. Shear	Drift	Max. Drift		Result
	Capacity Spectrum		0.440	1/78	1/67		PASS
	Response History	1995 Kobe	0.338	1/433	1/67		PASS
		2001 E.S.	0.346	1/369	1/67		PASS
	Irregularity	Comb.	2.78%				
		RC Only	1.10%				

Table 7. Results of the RC frame affixing technique, E-W direction.

			East-West Direction				
	Analysis Method		Is		Iso		Result
			1st level	2nd level	1st level	2nd level	
High Demand	JBDPA Method		0.87	0.81	0.80	0.60	PASS
	Analysis Method		B. Shear	Drift	Max. Drift		Result
	Capacity Spectrum		0.890	1/152	1/67		PASS
	Response History	1995 Kobe	0.545	1/703	1/67		PASS
		2001 E.S.	0.543	1/522	1/67		PASS
	Irregularity	Comb.	3.12%				
		RC Only	0.67%				
Low Demand	Analysis Method		Is		Iso		Result
			1st level	2nd level	1st level	2nd level	
	JBDPA Method		0.61	0.46	0.48	0.36	PASS
	Analysis Method		B. Shear	Drift	Max. Drift		Result
	Capacity Spectrum		0.460	1/72	1/67		PASS
	Response History	1995 Kobe	0.442	1/1530	1/67		PASS
		2001 E.S.	0.428	1/950	1/67		PASS
	Irregularity	Comb.	4.64%				
		RC Only	0.68%				

5. CONCLUSION

For this target building, the Polypropylene band wrapping technique was not enough to reach the required capacity. Both demand levels were too high, and the strength of the adobe masonry was too weak. Thus, the Polypropylene band wrapping technique was not feasible. The RC frame affixing technique increased strength and significantly increased ductility, making the building reach the required capacity. However, the adobe walls failed before reaching this point. This technique was feasible but required considerable structure, and the failure mode doesn't protect the adobe walls from extensive cracking. The Backside wall affixing technique increased ductility and strength before the failure of the adobe walls, making the building reach the required capacity. This technique was feasible, required less structure, and its failure mode protects the adobe walls from extensive cracking. Therefore, the backside wall affixing technique was the best retrofitting technique for this target building. As for the selection of the demand level, it depends on the projected habitability of the building. A low design level can provide a more economical and respectful retrofitting, but the building wouldn't be habitable. A higher design level can ensure the building's habitability but at a costlier and more aggressive solution.

ACKNOWLEDGEMENTS

This research was conducted during the individual study period of the training course "Seismology, Earthquake Engineering and Tsunami Disaster Mitigation" by the Building Research Institute, JICA, and GRIPS. I want to express my heartfelt gratitude to Dr. Shunsuke Sugano for his supervision throughout my entire Individual Study. I want to thank Dr. T. Azuhata and Dr. H. Suwada, for their valuable guidance. Thanks are also given to Dr. E. Peña (University of El Salvador, TAISHIN Project) and Dr. K. Meguro (University of Tokyo, PP-Band Study), for their valuable research in masonry that served as a reference in this study. I am also grateful to Dr. T. Saito (Toyohashi University of Technology) for allowing me to use his software tools for my study.

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