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Strengthening of Single Bay Tunnel Form Building using Steel Angle, Steel Plate and CFRP Under Out-of-Plane Cyclic Loading

Shamilah Anuar[1], Norhayati Abdul Hamid[2] and Mohd Hisbany Mohd Hashim[3]

[1, 2, 3]Universiti Teknologi MARA

Abstract**:** *A one-third scale of 3-storey single unit tunnel form building (TFB) was designed and constructed using non seismic design (BS8110) and tested under out-of-plane lateral cyclic loading. This prototype sample was tested at ±0.01%, ±0.1%, ±0.25%, ±0.5%, ±0.75%, ±1.00%, ±1.25%, ±1.5% and ±1.75% drift up to the strength degradation. TFB system is widely used around the world, including seismic prone areas. The seismic performance of this system differs for each country depending on its design, construction quality and the location of the epicenter. Most of the constructed TFB use the old version design code (prior 1970) of practice without seismic compatibility experience severe damage and collapse. Thus, seismic repair and strengthening become an alternative method to enhance the seismic capacity of existing structures. The experimental work to retrofit a 3-storey TFB using a combination of steel angle, steel plate and carbon fiber reinforce polymer (CFRP) fabric was conducted. The lateral strength, stiffness, ductility, energy absorption and visual observation were compared. The experimental results showed that this technique increased by 31% of lateral strength and 51% of energy absorption. It can be concluded that this combination method can be adopted as a rehabilitation technique for the existing building in Malaysia.*

Keywords: *Strengthening, lateral strength, energy absorption, rehabilitation.*

1. Introduction

Frequent seismic events have occurred in the countries that are located within the Pacific Ring of Fire. This phenomenon has triggered the sleeping fault line in West Malaysia. Several fault lines in Malaysia are located at Bukit Tinggi, Kuala Pilah and Jerantut [1]. Each ground motion activity will create a new crack which will exacerbate the existence of sleeping fault lines. The worst-case scenario is that, all buildings in Malaysia are designed without considering any earthquake loading. Thus, the safety level of the building in Malaysia, especially high rise building, is starting to be questioned. Therefore, the repair and retrofit method should be investigated and proposed a new technique in order to restore the lateral strength and ductility of existing building.

Even though modern codes of practice are used in designing and constructing of new buildings, however, the structural performance is still in doubt because there is no specific formula to evaluate the codes [2]. The current code of practice (BS8110) has been used to construct almost all buildings in Malaysia. Several apartment and high rise buildings in Penang and Johor suffered hairline crack and spalling of concrete cover due to the 2004 and 2012 Sumatra Earthquake under long-distant earthquake effect. Furthermore, monolithic wall panels suffered moderate to severe damages during past seismic events [3]**.** Therefore, various repair and retrofit techniques have been studied by previous researchers around the world. El-Sokkary et al. studied on the rehabilitation of RC shear wall using fiber reinforce polymer (FRP) to increase the flexural and shear capacities of the 6th storey wall panel [4]. Anuar et al studied the performance of 3-storey TFB under in-plane lateral cyclic loading [5]. The visual observation indicated that the wall-slab joint and shear wall of the first and second floor suffered severe cracks. The combination of steel plate, steel angle and CFRP sheet was adopted as the repair and retrofit techniques. The lateral capacity, energy absorption and ductility increased significantly. Meanwhile, the assortment of repair and retrofit materials were investigated by previous researchers such as steel plate, steel

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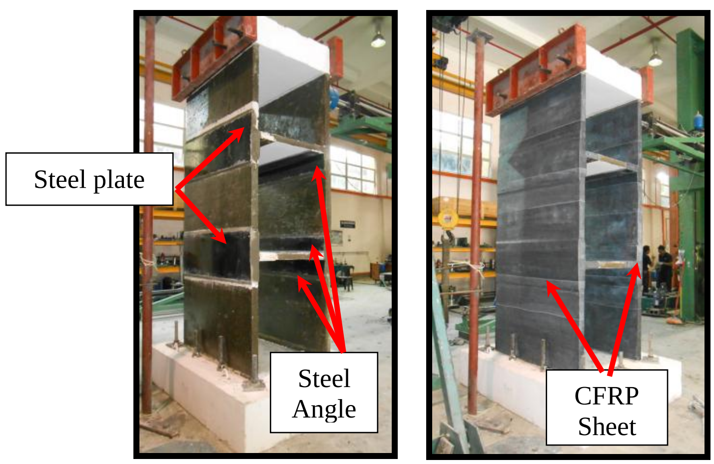
fiber reinforce concrete (SFRC), additional shear wall and base isolator to restore the strength capacity of the structure [6], [7], and [8].

This paper concentrates on repairing and retrofitting of the damaged shear wall and wall-slab joint. The combination retrofit methods were studied in order to determine its feasibility for tunnel form building to provide high lateral load resistance. Steel angle, steel plate and carbon fiber reinforce polymer were applied and wrapped to the tunnel form building (TFB) before they were tested under the out-of-plane lateral cyclic loading. The experimental results obtained before and after the repair and retrofit steps were compared**.**

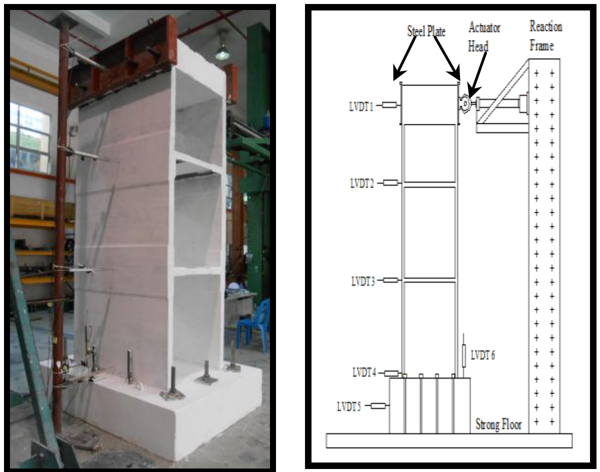
2. Materials And Method

In this paper, a single unit of 3-storey tunnel form building was designed, constructed and tested under out-of-plane cyclic loading. The testing process consists of two stages. In the first stage, the tunnel form building was tested until the lateral strength had achieved the ultimate load. Load was applied to the specimen using control displacement method. The loading were imposed at ±0.01%, ±0.1%, ±0.25%, ±0.5%, ±0.75%, ±1.00%, ±1.25%, ±1.5% and ±1.75% drift until they reached the strength degradation.

In the second stage, the same sample was repaired and strengthened using the combination of steel angle, steel plate and carbon fiber reinforced polymer (CFRP). In the first step, the selected location of retrofitting was grinded before steel plate, steel angle and CFRP was attached and placed at the damaged area. The location of the steel plate and steel angle was based on the previous crack during the first stages (original state) of testing located at the wall-slab joint. Six steel angles were attached to the wall-slab connection and four steel plates were patched to the outer wall as shown in Fig. 1 (a). Then, a single layer of CFRP fabric was wrapped together with steel angle and steel plate to enhance the lateral strength of the tunnel form building system as shown in Fig. 1 (b). After applying steel angle, steel plate and CFRP fabric, the specimen was painted white as shown in Fig. 1 (c). Later, the TFB was re-tested up to failure using similar approach as the previous testing on non-retrofitting the tunnel form building. The size of angle steel was 1200mm x 150mm x 6mm. Meanwhile, the size of steel plate was 1200mm x 400mm x 6mm, which was applied to strengthen the wall-slab interface. In this paper, the application of shear wall and the connection of wall-slab were intended for repairing and strengthening purposes. Once the retrofitting process was completed and finished, the experimental set-up using instruments such as LVDTs and strain gauge were installed and placed at the left hand side of the tunnel form building and foundation beam as shown in Fig. 1 (d).



(a) (b)



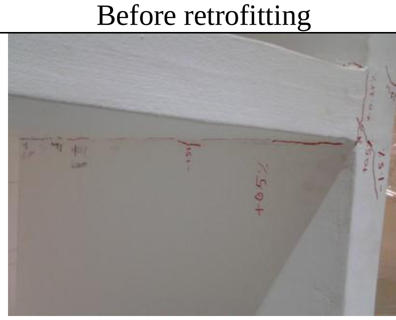
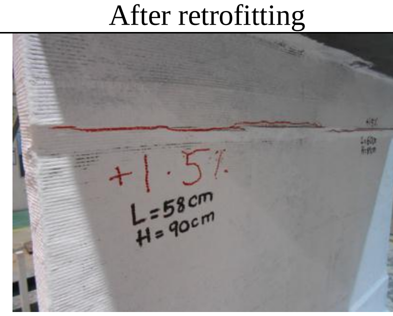
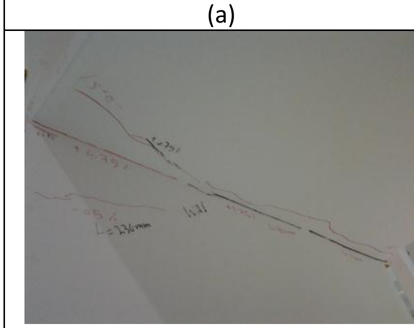
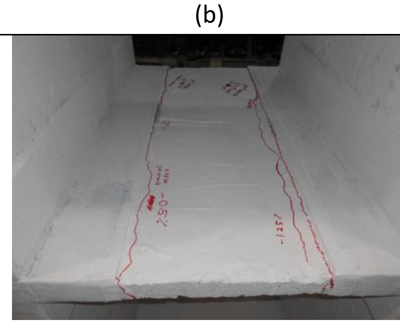
(c) (d)

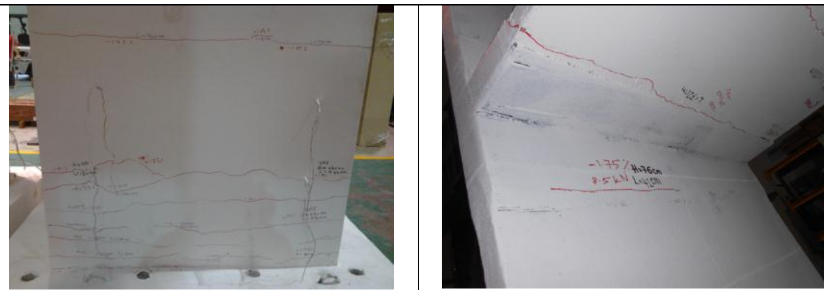
Fig. 1: Repairing and strengthening process for tunnel form building (TFB); (a) TFB patched with steel angle and steel plate, (b) CFRP wrapped to the whole wall of TFB, (c) white-painted TFB, (d) testing the set-up of TFB.

3. Results And Discussion

3.1. Visual observation on damages

Crack patterns were observed before repairing and retrofitting, which elongated more along the shear wall compared to after repairing and retrofitting. Cracks were also found to be propagated along the wall-slab joint that occurred during the initial testing (before retrofit). During the testing after repairing and retrofitting, cracks were only observed at the non-retrofit area such as the slab (upper and bottom). Fig. 2 (a) shows the occurrence of crack at the wall-slab joint of the first floor level obtained before strengthening. Fig. 2 (b) indicates the CFRP sheet shredding at the first floor level shear wall. Fig. 2 (c) shows the propagation of cracks along the wall-slab joint of the second floor level. Fig. 2 (d) illustrates the occurrence of cracks at the first to second floor slab (upper surface). Fig. 2 (e) shows the elongation cracks at the outer surface of the first floor shear wall. Fig. 2 (f) indicates the cracks appeared at the lower surface of the first to second floor slab.

Before retrofitting	After retrofitting
 (a)	 (b)
 (c)	 (d)

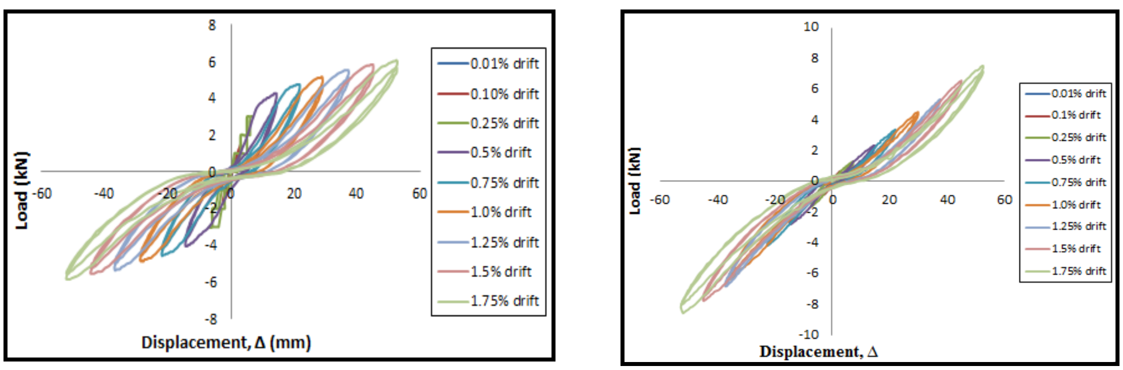


(e) (f)

Fig. 2: Crack patterns observed during testing: (a) the occurrence of crack at the wall-slab joint of the first floor, (b) CFRP sheet shredding at 1.5% drift, (c) crack pattern observed at the second floor wall-slab joint, (d) crack propagated along the slab area (upper part of second floor, (e) crack elongated along the shear wall of the first floor (outer part), (f) crack appeared at the shear wall and slab (bottom part) of the first floor level.

3.2. Hysteresis loop

Fig. 3 shows the comparison of lateral strength of tunnel form building after and before it was retrofitted. The significant increment of lateral strength was found in the pulling phase with 32% compared to before retrofitting. Meanwhile, an increment of 21% for the pushing phase was obtained after repairing and retrofitting. This indicates that the combination of steel angle, steel plate and CFRP gives a significant increment in the lateral load. Furthermore, the easy process of this rehabilitation technique will become an effective method to be adopted in enhancing the seismic resilience of high rise building, especially for residential building in order to reduce human fatalities during seismic events in the future.



(a) Before retrofitting b) after retrofitting

Fig. 3: Hysteresis loops obtained before and after retrofitting of the tunnel form building

3.3. Stiffness and ductility

The comparison of stiffness and ductility of tunnel form building before and after retrofitting in pushing and pulling directions are recorded in Tables 1 and 2, respectively. It seems that in the pushing direction, the ductility obtained after retrofitting was found to have a significant decrease of approximately 50% compared to before retrofitting. However, the pulling direction, the tunnel form building seemed to undergo only 3% reduction in ductility. This means that, the combination of these rehabilitation techniques is not enough to cater for the out-of-plane lateral cyclic loading of TFB. An additional shear wall may be used in the repairing and retrofitting process in order to increase the stiffness and rehabilitation of TFB in future research work.

TABLE I: STIFFNESS AND DUCTILITY OF TFB OBTAINED BEFORE AND AFTER RETROFITTING IN PUSHING DIRECTION

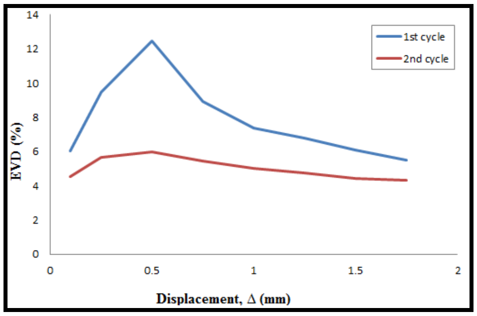
Pushing direction	Drift (%)	Elastic stiffness, Ke (kN/mm)	Secant stiffness, Ksec (kN/mm)	Ductility μ
Before retrofit	0.01	3.00	0.00	0.00
	0.1	0.5	0.00	0.13
	0.25	0.43	0.00	0.32
	0.5	0.30	0.00	0.66
	0.75	0.00	0.07	1.00
	1.00	0.00	0.06	1.33
	1.25	0.00	0.04	1.71
	1.50	0.00	0.04	2.07
	1.75	0.00	0.03	2.41
After retrofit	0.01	0.50	0.00	0.00
	0.01	0.22	0.00	0.10
	0.25	0.18	0.00	0.25
	0.5	0.16	0.00	0.50
	0.75	0.15	0.00	0.73
	1.00	0.00	0.14	1.00
	1.25	0.00	0.11	1.25
	1.50	0.00	0.16	1.50
	1.75	0.00	0.13	1.75

TABLE 2: STIFFNESS AND DUCTILITY OF TFB OBTAINED BEFORE AND AFTER RETROFITTING IN PULLING DIRECTION

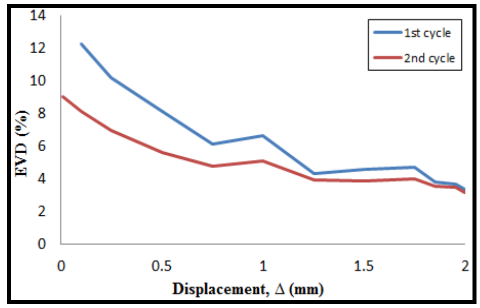
Pulling direction	Drift (%)	Elastic stiffness, Ke (kN/mm)	Secant stiffness, Ksec (kN/mm)	Ductility μ
Before retrofit	0.01	1.00	0.00	0.01
	0.1	0.67	0.00	0.12
	0.25	0.43	0.00	0.32
	0.5	0.28	0.00	0.66
	0.75	0.00	0.07	1.00
	1.00	0.00	0.04	1.31
	1.25	0.00	0.06	1.69
	1.50	0.00	0.02	2.04
	1.75	0.00	0.01	2.39
After retrofit	0.01	0.75	0.00	0.01
	0.01	0.29	0.00	0.13
	0.25	0.22	0.00	0.32
	0.5	0.19	0.00	0.66
	0.75	0.00	0.18	1.00
	1.00	0.00	0.17	1.59
	1.25	0.00	0.27	1.66
	1.50	0.00	0.12	2.00
	1.75	0.00	0.12	2.31

3.4. Equivalent viscous damping (EVD)

The comparison of the percentage of equivalent viscous damping (EVD) before and after retrofitting is shown in Fig. 4. Energy absorption of TFB during the first cycle of testing started at the minimum value, but increased and exceeded 12% for the first cycle compared to the second cycle. Meanwhile, after retrofitting, TFB seemed to absorb higher energy for both cycles compared to before rehabilitation. However, it observed that the EVD decreased as the drift increased. This indicates that these repair techniques provides a significant increment of EVD percentage during the early stage of the second time testing especially in the first cycle. The materials used did not absorb more energy compared to before retrofitting. Therefore, an additional shear wall with new BRC wire mesh should be used in order to increase the energy absorption of tunnel form building.



(a) Before retrofitting



(b) After retrofitting

Fig. 4: Equivalent viscous damping (EVD) of the first and second cycles acquired before and after strengthening.

4. Conclusion

The main objective of the repair and retrofitting technique is to increase and enhance the load resistance capability of the structure itself in order to survive under future seismic excitation. Furthermore, by increasing the resilience of building, human casualties during ground motion phenomenon can be reduced. In this experimental work, the combination of steel angle, steel plate and CFRP was selected due to the minimum disruptions to the occupant, require short duration of installation and easy to be applied. These rehabilitation techniques had increased the lateral strength and energy absorption of TFB even after being tested for three times. The benefit of using the CFRP sheet is avoiding the spalling of concrete cover during the shaking activity. This phenomenon can prevent any injuries and give enough time for occupants to escape from the damaged building. This experimental work indicates that even though TFB has been hit 3 times by seismic strikes, this structure can still survive without major damages. This shows that the combination of these materials can be adapted as a preparation for our existing high-rise structure to face any ground motion in Malaysia in the future.

5. Acknowledgement

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