

Comparison of Double Unit Tunnel Form Building before and after Repair and Retrofit under in-Plane Cyclic Loading

S. A. Anuar, N. H. Hamid, M. H. Hashim, S. M. D. Salleh

Abstract—This paper present the experimental work of double unit tunnel form building (TFB) subjected to in-plane lateral cyclic loading. A one third scale of 3-storey double unit of TFB is tested until its strength degradation. Then, the TFB is repaired and retrofitted using additional shear wall, steel angle and CFRP sheet. The crack patterns, lateral strength, stiffness, ductility and equivalent viscous damping (EVD) were analyzed and compared before and after repair and retrofit. The result indicates that the lateral strength increases by 22% in pushing and 27% in pulling direction. Moreover, the stiffness and ductility obtained before and after retrofit increase tremendously by 87.87% and 39.66%, respectively. Meanwhile, the energy absorption measured by equivalent viscous damping obtained after retrofit increase by 12.34% in pulling direction. It can be concluded that the proposed retrofit method is capable to increase the lateral strength capacity, stiffness and energy absorption of double unit TFB.

Keywords—Crack pattern, stiffness, ductility, equivalent viscous damping.

I. INTRODUCTION

TUNNEL Form Building system (TFB) is also known as Industrialized Building System (IBS) which are prepared and casting at site. This system provides a good lateral load resistance, faster construction, less formwork and good quality of finishes. From previous research work the structural performance of tunnel form building under earthquake excitations is varied (from good to moderate damage). Some buildings behave well and some are not due to its irregularity plan, open spaces, construction quality, adequacy of reinforced detailing and the location of building from epicenter of earthquake.

Up to date, the usage of tunnel form building for high rise buildings and condominium gained popularity in Malaysia. However, the design of this type of building did not consider earthquake loading under BS8110. In addition, the existence of fault line in Sabah and Sarawak could cause more cracks in RC building. This phenomenon will give a greater consequence if severe or moderate earthquake strike in East and West Malaysia for high rise building especially in urban areas. There are many condominiums and apartments were

constructed using tunnel form building. These buildings could be damaged after the earthquake strike.

Thus, repair and retrofit method can be implemented to enhance and restore the capability of the buildings to be more resilience under moderate or severe earthquake. Whilst, various materials and techniques of retrofitting method which had been adopted in high seismic region such as Japan, New Zealand, Turkey and Indonesia. Recently, assorted of intervention techniques of retrofitting have been introduced such as infilled brick wall, jacketing technique, additional of shear wall, cross bracing of frame, wrapping of carbon fiber reinforce polymer CFRP either sheet or plate to the damage specimen and the latest is alloy shape memory (SMA).

Furthermore, the additional external shear wall for strengthening method can improve the lateral strength capacity of 2-storey frame system [1]. Moreover, repair and retrofit of wall and frame using infill method gained popularity which can increase the lateral strength and stiffness capacity of structures [2]. Other materials which commonly used for repair and retrofitting of damage structures components is CFRP (Carbon Fibre Reinforced Polymer). CFRP has been used as repair and retrofitted of beam-column joint of precast school building under in-plane lateral cyclic loading [3]. Experimental results show that CFRP and steel plate can increase the lateral strength and ductility of beam-column joint. Moreover, SFRC which mixed with wet concrete and apply for the beam-column joint also can reduce the crack and increase the lateral strength of the structures [4].

However, there is lack of study on retrofitting the tunnel form building as compared to the beam-column and column-wall structural element. Initial study on performance of tunnel form building subjected to lateral cyclic loading was conducted by Balkaya and Kalkan [5] and followed by Yuksel and Kalkan [6]. Al-Aghabari et al [7] study on the performance of wall-slab under lateral cyclic loading using anchorage bracing and cross bracing joints. These studies indicate that a lot of cracks were occurred at the wall-slab joint and shear wall interface. Further study on repairing and retrofitting a single unit of 3-storey TFB using steel angle, steel plate and CFRP sheet subjected to in-plane lateral cyclic loading was carried out [8]. Therefore, the main objective of this research is to repair and determine the seismic performance of a 3-storey double unit tunnel form building under in-plane loading. The comparison of specimen before and after repair is made in term of strength capacity, stiffness and equivalent viscous damping (EVD). In addition, the visual

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observation on crack initiation and propagation observed, recorded and measured.

II. METHODOLOGY

A one third scale of 3-storey double unit tunnel form building (TFB) was designed using BS8110, constructed and tested under out-of-plane cyclic loading. This specimen has been tested using two cycles for each drift until the structure failed and achieved strength degradation. The testing was conducted using control displacement method where the target drifts are determined. It started at $\pm 0.01\%$, $\pm 0.1\%$, $\pm 0.25\%$, $\pm 0.5\%$, $\pm 0.75\%$ until $\pm 1\%$ drift and each drift consists of 2 cycles in pushing and pulling direction. The testing was conducted until the structure loss its strength capacity and achieved the strength degradation.

After testing, the similar TFB was repaired and retrofitted using the combination of additional shear wall, steel angle and CFRP sheet attached to the wall. The same size of shear wall were constructed to the existing outer layer of wall for both side left and right as shown in Fig. 1 (a). The overall size of wall including additional wall is 1200mm x 2850mm x 100mm. The wire mesh BRC-8 was placed at middle of wall with 80 mm spacing vertical and horizontally. Twelve (12) steel angles were attached to the wall-slab joint of the first and second floor tunnel form building as demonstrated in Fig. 1 (b). The locations of these steel angles are based on the previous crack obtained from the initial testing. Later, a single layer CFRP sheet was wrapped to the first and second floor wall as shown in Fig. 1 (c). Finally, the whole double unit TFB was painted with white colour to easily captured any rip of CFRP sheet and cracks during testing as shown in Fig. 1 (d).

III. COMPARISON OF RESULTS

A. Visual Observation on Damages

Table I shows the overall crack patterns obtained from visual observation captured before and after retrofitting. The specimen started to crack at $\pm 0.25\%$ drift before retrofitting and $\pm 0.5\%$ drift after retrofitting. Before retrofitting, the crack started to appear at the edge of the wall interface and elongated along the wall during the next drift. However, after retrofitting, the cracks started to appear at $\pm 0.75\%$ drift. After retrofitting, there is no elongation of crack occur as compared before retrofit at $\pm 0.5\%$ drift. This is because the CFRP sheet which wrapped to the shear wall surface mitigates the falling of concrete as previous testing. The ability of CFRP sheet to absorb the energy and release it in pushing and pulling direction has reduced the continuation of crack from each drift.

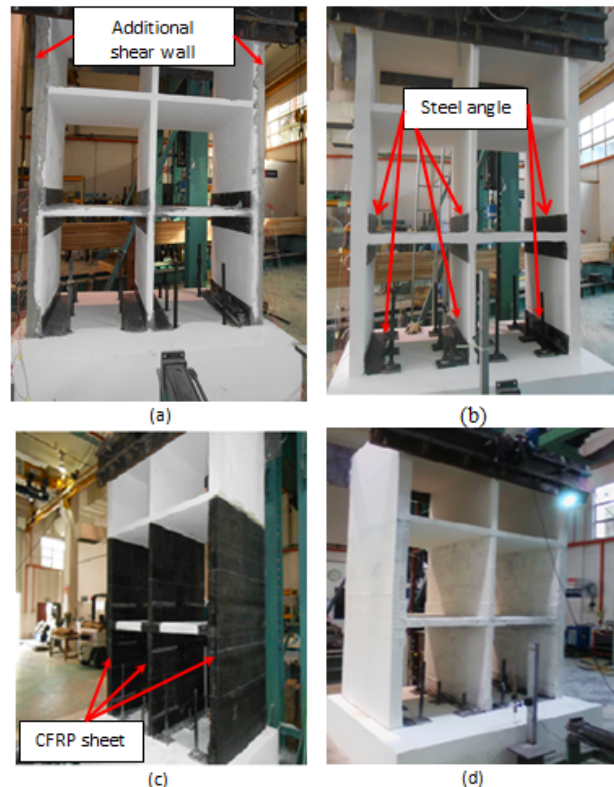


Fig. 1 Repair and retrofit process of double unit TFB (a) the completion of new additional shear wall, (b) the installation of steel angle, (c) the completion of wrapping CFRP sheet on shear wall interfaces and (d) painting the CFRP sheet with white colour

TABLE I
VISUAL OBSERVATIONS OF CRACK PATTERN BEFORE AND AFTER
RETROFITTING

Drift (%)	Before retrofit	After retrofit
0.01	-No crack observed	-No crack observed
0.1	Hairline crack occurred on the wall-slab joint of the first floor.	-No crack observed
0.25	-Hairline crack occurred during 24kN of lateral load on the wall-slab interface.	-No crack observed
0.5	-Crack occur and elongated under the wall-slab joint of the first floor level of shear wall.	-The first crack started to occur in the wall foundation intersection (wall C) at 51.53kN of lateral load.
0.75	-Cracks started to appear at the edge of the second floor wall (inner).	-A crack found on the wall-foundation joint of wall B
1.0	-The propagation of crack along the inner surface of the wall (first floor) and diagonal crack started to form in the middle of the wall.	-Most of the cracks seem to be appearing at the edge of first floor shear wall B (middle wall) at the first floor level.

B. Hysteresis Loop

Fig. 2 shows the comparison of hysteresis loop of tunnel form building before and after retrofitting up to $\pm 1.0\%$ drift. The enclosed hysteresis loops after retrofitting is bigger than the hysteresis loop before retrofitting. The usage of additional shear wall, angle steel and CFRP sheet give a higher value of lateral strength as compared before retrofitting. The greater

increment of lateral load obtained from the first cycle in pushing direction after retrofitting is 90kN as compared before retrofitting of 70kN. A similar pattern in pulling direction (first cycle) where the lateral load after retrofitting is higher (98kN) than before retrofitting (72kN). It indicates that this retrofit method could increase the lateral strength capacity of TFB in pushing and pulling direction for the first and second cycle.

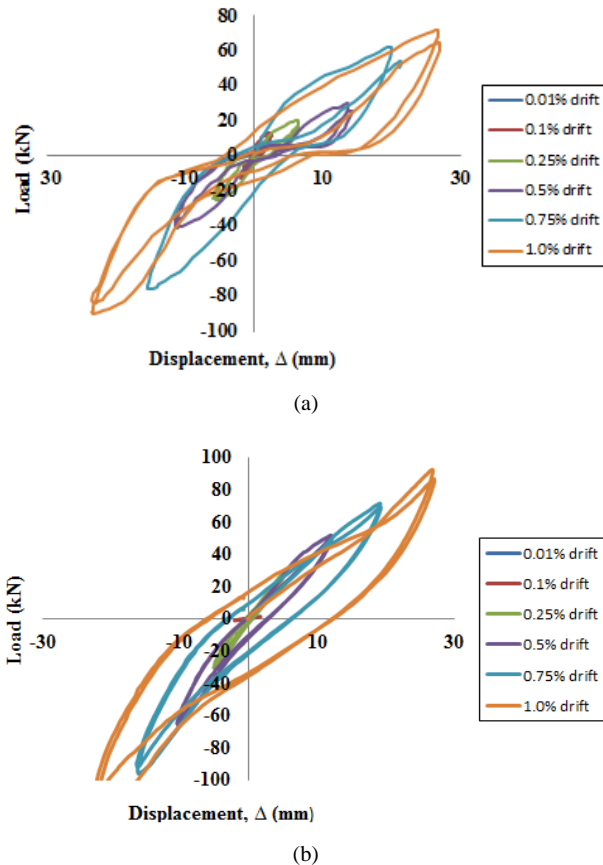


Fig. 2 Hysteresis loop (a) before retrofitting and (b) after retrofitting

C. Stiffness and Ductility

The additional shear wall, steel angle and CFRP sheet have increased 87.87% the stiffness of double unit tunnel form building. The specimen seems to be more stiffened using this proposed technique of repair and retrofit. This is because the CFRP sheet wrapped to the wall surface significantly contributes the strength for the structure to resist the lateral load. The fine fabric in CFRP sheet provides the extra steel reinforcement for the TFB and reinstatement the initial stiffness of the specimen. Table II indicates the percentage different of stiffness obtained before and after retrofit for each drift.

TABLE II
STIFFNESS BEFORE AND AFTER RETROFIT

Drift (%)	Stiffness		Percentage Different (%)
	Before	After	
0.01	12.59	28.35	55.59
0.1	5.69	26.00	78.13
0.25	3.23	5.54	41.67
0.5	2.18	3.25	32.68
0.75	5.27	2.77	-90.44
1.00	0.33	2.75	87.87

Meanwhile, the ductility of double unit tested under in-plane lateral cyclic loading found to be increased about 39.66%. Meaning to say that, the combination materials for retrofitting in this experimental work could help TFB to become more ductile and stronger during the second time of testing due to the additional BRC-A8. Table III shows the value of ductility for each drift together with percentage different before and after retrofitting. The overall ductility obtained before retrofitting is 1.35 and after retrofitting is 2.23.

TABLE III
DUCTILITY BEFORE AND AFTER RETROFIT

Drift (%)	Stiffness		Percentage Different (%)
	Before	After	
0.01	0.01	0.03	60.77
0.1	0.12	0.14	19.85
0.25	0.32	0.45	29.33
0.5	0.69	1.00	31.05
0.75	1.00	1.60	37.31
1.00	1.35	2.23	39.66

D. Equivalent Viscous Damping (EVD)

Fig. 3 shows the comparison of equivalent viscous damping (EVD) before and after retrofitting for both cycles. The EVD for the first cycle before retrofitting seems to be decreased as the drift increase. EVD first cycle after retrofitting seems to be increased as the drift increased. The percentage increment between before and after repair for the first cycle is not much differing. However, the EVD for the second cycle, before and after repair seems to have similar pattern. It is increased as the drift increase, but EVD after repair increased 12.34% from before repair. In fact, even though EVD after repair started at lower value as compared with before repair, but it manages to increase much more higher than before repair.

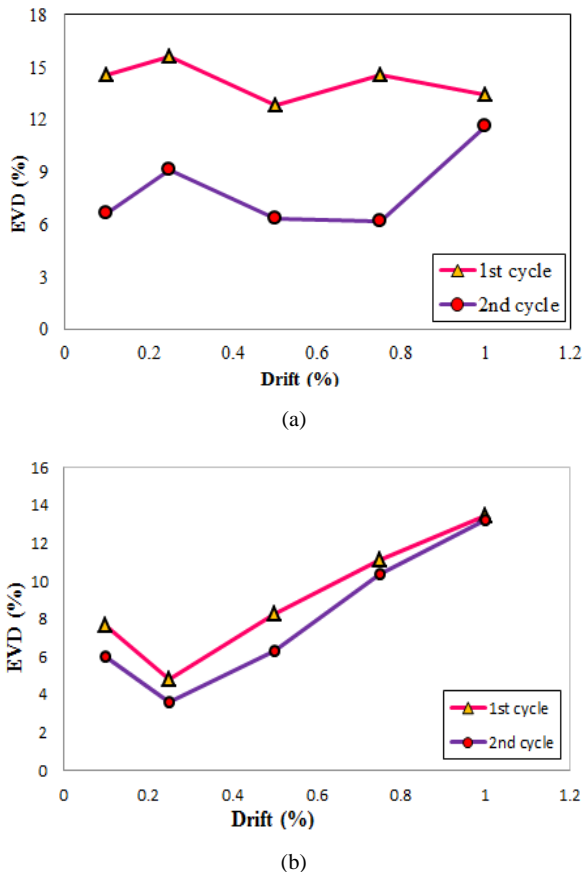


Fig. 3 Equivalent viscous damping (a) before retrofitting and (b) after retrofitting

IV. CONCLUSION

The proposed repair and retrofit method in this experimental work have tremendously increased the strength capacity, stiffness and ductility of double unit TFB. This indicates that the additional shear wall with new BRC wire mesh enable the damage TFB to have a significant restoration during the second time of testing. With the combination of steel angle and CFRP sheet, the specimen experiences almost the full restoration from the initial of testing. This repair and retrofit technique can be applied to the existing structure without involving any major alteration to the overall structure. Therefore, it can be concluded that this method is efficient, save time consuming and effectively in enhancing the structure that susceptible to the earthquake events.

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