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Seismic response of precast and IBS buildings under earthquake attacks

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Abstract. Poor performances of precast buildings during earthquakes were due to inadequate connections between the structures components, insufficient seating and anchorage and poor workmanship and quality materials used. It is important to investigate their seismic performance by conducting experimental work, analyzing the data and modelling them using nonlinear time history analysis of the earthquakes. Three types' structural components of precast structures and Industrialized Building System (IBS) were designed, constructed, tested, analyzed and modelling in this chapter. There structural components are precast shear-key wall panel, beam-column joints and tunnel form building system. All these specimens were tested under in-plane lateral cyclic loading. The seismic performance parameters such as lateral strength capacity, stiffness, ductility and equivalent viscous damping were evaluated using the measured hysteresis loops from experimental work. The findings from this research work can be implemented and enforced by government and local authorities to pay special attention to joint detailing of precast structures components while constructing the precast buildings. The design concepts and detailing of the jointing precast structural components contribute significantly to the overall seismic performance of precast buildings under earthquakes excitations. A lot of structural damages occurred during earthquakes due to not using the current seismic code of practice and poor detailing especially at the jointing system.

1. Introduction

Precast tilt-up buildings become the most vulnerable structures when subjected to earthquake excitations. This is due to lack of attention given to the detailing at joints such as wall-foundation interfaces, wall-column interfaces and beam-column interfaces. Many structural failures occurred at these interfaces because the vertical and horizontal loads from dead load, live load, wind load and earthquake load are failed to transfer them from the joints to the foundation. The first major destructive earthquake was occurred on the tilt-up buildings during the 1964 Alaska Earthquake with M9.2 scale Richter where the collapse of these buildings at Elmendorf Air Force Base, Anchorage Alaska [1]. Then, followed by the 1971 San Fernando Earthquake with M6.6 scale Richter caused severe damage to precast wall panels and roofs of the Vector Electronics Building, San Fernando, California [2]. Consequently, the 1994 Northridge Earthquake caused the connection failure between precast wall panels and precast beams interfaces of the parking garage [3]. Later on, the 1999 Kocaeli Earthquake caused partial collapse of the three agricultural warehouses at Arifiye, Turkey which made from precast wall panels [4]. Subsequently, the 2001 Bhuj Earthquake had caused a total number of 106 precast schools buildings were totally collapse in Bhuj, India [5]. The collapsed of some precast school buildings occurred due to poor quality of workmanship, lack of detailing at joints, did not design and construct according to the current seismic code of practice of the particular regions. Three types of RC buildings and structural components were designed, constructed, tested under in-plane lateral cyclic loading and analysis their performance are presented. They are single bay double-storey house was constructed using precast shear key wall panel, beam-column joints with corbels and three-storey tunnel form building (TFB) were designed using BS8110 constructed and tested under in-plane lateral cyclic loading. All the specimens were observed the structural damages, recorded the in-plane lateral displacement, lateral load and analysed the hysteresis loops for lateral strength capacity, elastic stiffness, secant stiffness, displacement ductility and equivalent viscous damping.

2. Double-storey Residential Houses Using Precast Shear-Key Wall Panels

Sustainability of the residential houses is very important especially during maintenance and repairing stage due to frequent earthquakes attacks. Nowadays, many residential houses in Malaysia are constructed using modular system and it requires by adopting the tilt-up construction technique for assembling the precast structural components to become the precast buildings or houses. Furthermore, almost all the residential houses in Malaysia are designed using BS8110 where there is no provision for earthquake loads. Besides that, the quality of the construction is still questionable especially in terms of workmanship, quality of the materials used and lack of supervision at construction site. In order to solve these kinds of problems, tilt-up construction method is introduced in the construction of precast buildings to increase the quality of the houses. This technique has been developed in the United States since 1908 and widely used in Malaysia from 1960’s for the construction of apartments, residential houses, schools, hypermarkets, commercial/industrial buildings and others [6,7]. Most of the tilt-up precast wall panels or load bearing walls have the potential to carry roof loading without any columns [8]. If the wall is slender, significant transverse shear reinforcement is required to resist horizontal shears arising from seismic and wind loading. However, tilt-up wall panels are amongst the most vulnerable type of structures under ground motion because inadequate detailing at their joints, structural integrity and quality of workmanship [9]. Even though precast wall hollow core panel is vulnerable to earthquake but it can be designed in such as that it can resist earthquake excitation by using the concept of Damage Avoidance Design and rocking structures [10]. It is evidences through a good and excellent experimental results using a hybrid precast hollow core wall tested under biaxial lateral cyclic loading and a multi-panel precast hollow core walls under in-plane lateral cyclic loading [11, 12]. In Malaysia, there are various types of precast wall panels such precast hollow core walls, solid precast wall panel, precast shear key wall panels and lightweight precast wall panel are commonly used in the construction of residential houses. Nevertheless, these types of wall panels are designed only subjected to gravity and not design to resist earthquake loading. The seismic assessment of precast shear key wall panel showed that this type of wall is not survive under MCE (Maximum Considered Earthquake) and experience partial collapse of this type of house [13]. Therefore, the aim of this chapter is to explain the seismic performance of precast shear key walls by constructing double-storey residential house and tested under in-plane lateral cyclic loading. The detail model and analysis on behavior factor and displacement estimation of precast shear key wall panel were performed by Tiong et. al., [14]. In Malaysia, most of RC double-storey houses are designed using BS 8110 by considering the gravity load only and disregard the impact of lateral load such as earthquake loads. Figure 1 displays two precast walls connected to each other using cast-in-situ beam and slab concrete. Figure 2 exhibits the construction of precast double-storey house using steel scaffoldings, precast shear-key wall panels, cast-in-situ floor slab and cast-in-situ beams.

Figure 1. Cast-in-situ beams and slabs are used to joint two wall panels.

Figure 2. Construction of single bay double-storey house in the laboratory.

Table 1 tabulates the experimental results of the stiffness and ductility of shear key for WALL1 and WALL 2. The average elastic stiffness for shear key of WALL2 is 21.27 kN/mm and secant stiffness is 9.7 kN/mm. In order for the structure resist earthquake loading, the ductility of the building should range from 3 to 6 but the ductility for this specimen is 2. Therefore, this type of building did not survive under strong earthquake attack it is less than 3.

Table 1. Stiffness and ductility for WALL1 and WALL 2

Drift (%)	Stiffness (WALL1)	Ductility (WALL 1)	Stiffness (WALL 2)	Ductility (WALL 2)
0.05	K_e= 29.3	μ = 0.17	K_e= 22.22	μ = 0.17
0.1	K_e= 27.11	μ = 0.33	K_e= 36.4	μ = 0.33
0.2	K_e= 19.5	μ = 0.67	K_e= 17.11	μ = 0.67
0.3	K_e= 9.33	μ = 1.00	K_e= 9.33	μ = 1.00
0.4	K_{secant}= 3.78	μ = 1.33	K_{secant}= 10.22	μ = 1.33
0.5	K_{secant}= -3.78	μ = 1.67	K_{secant}= 4.44	μ = 1.67
0.6	K_{secant}= -8	μ = 2.00	K_{secant}= -14.44	μ = 2.00

3. Precast Beam-column Joints With Corbels

Beam-column joint is the crucial part in a RC building where the vertical and horizontal loads met and transfer the load to the foundation. In RC buildings, the failure of beam-column joint was observed and causing the collapse of building after earthquake attack. Beam-column joints played an important role in determining the ductile of moment-resisting frames [16,17,18]. Therefore, the integrity of structural in RC building should be safe and stable under minor, moderate and severe earthquake excitations. Ductile beam-column joint is closely related to the detailing of transverse and longitudinal bar, poor workmanship issue, the placement of reinforcement in joints and usage of seismic code of practice. The failures of beam-column joints in RC building were observed in some of catastrophic failures during past earthquake events. A good example was the 1999 Kocaeli Earthquake where joint shear failures were observed during the earthquake. Joint shear failures may result in non-ductile performance of reinforced concrete moment-resisting frames which were designed and constructed before the development of current seismic codes [19]. In New Zealand, large numbers of reinforced concrete framed buildings which were built before 1970's were reported to moderately and severely damage in 2011 Christchurch Earthquake [20]. Precast structure seems to be more practical nowadays to overcome problems pertaining construction productivity and the quality of construction products, despite the shortage of skilled workers [21]. Precast concrete framed structures are more popular as compared to prefabricated steel framed structures due to price matters even though steel structures are relatively lighter in mass and lacking in stiffness [22]. Precast concrete products are

widely adopted in Malaysia started in the year between 1960s and 1980s, due to the rising demand from public housing projects including of low and medium cost apartments [23]. In Malaysia, British Standard (BS8110) was used for reinforced concrete design including precast and prestressed members which do not specify any requirement for seismic design or detailing of reinforced concrete structures [24, 25, 26, 31]. Until 2004, there has been no record of earthquake damage in Malaysia and Singapore regions although ground motions due to long distance earthquakes centred in Sumatra have occurred [27]. Devastated earthquake event which destroyed Aceh, Indonesia in 2004 has triggered tsunamis leads to casualties in the area of Penang and Kedah in Malaysia. Therefore, the performance of beam-column joints in precast reinforced concrete structures needs to be tested because the connections are strongly needed not only to transfer loads but provide continuity and overall monolithic behavior in the entire reinforced concrete structure. Figure 3 shows the super-assemblage of precast exterior beam-column joints with corbels which was ready for testing under in-plane lateral cyclic loading. Meanwhile, Figure 4 shows the graph of loading regime
(inter-storey drift versus cycle) which will be applied for testing the specimen starting from ±0.01%, ±0.1%, ±0.25%, ±0.5%, ±0.75% and ±1.0% drift until failure.

Figure 3. Super-assemblage of precast beam-column joint is ready for testing

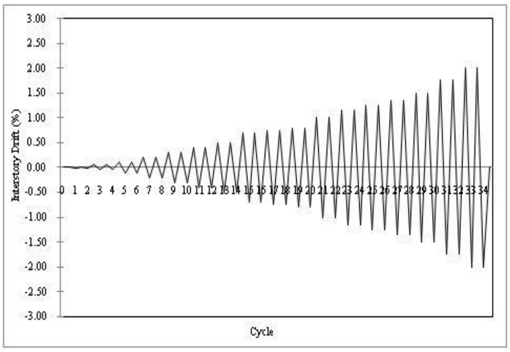
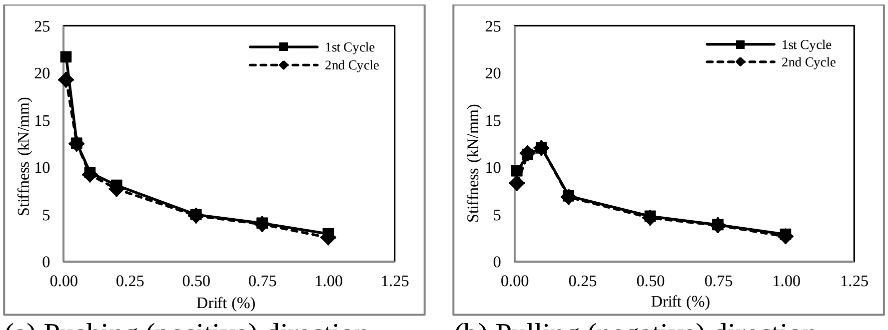


Figure 4. Loading regime for specimen testing under in-plane lateral cyclic loading

Figure 5(a) and (b) shows the stiffness degradation traces of specimen in pushing (positive) and pulling (negative) directions, respectively, for both cycles. At both directions, the specimen exhibits non-linear behavior starts from ±0.75% inter-story drift. The first cycle for both directions exhibits higher stiffness values as compared to second cycle. The specimen also demonstrates higher stiffness degradation at pulling direction as compared to pushing direction.



(a) Pushing (positive) direction (b) Pulling (negative) direction

Figure 5. Stiffness degradation traces of tested specimen

4. Tunnel Form Buildings as Industrialized Building System (IBS)

Tunnel form building (TFB) is an Industrialized Building System that comprises walls and slabs as main structural components using modular system approach. Shear walls in TFB can provide high stiffness and lateral strength to cater for large amount of seismic loading and minimize the damage of the structure [28]. Many countries such as Turkey, Japan, New Zealand, California and Malaysia had used TFB system to construct medium and high rise buildings. Even though some of these countries are located in high seismic regions but these buildings had survived under several earthquake events such as Kocaeli Earthquake with 7.4 magnitude, Duzce Earthquake with 7.2 magnitude, and Bingol Earthquake with 6.5 magnitude in Turkey starting from 1999 to 2004 [29]. This indicates that TFB building is not vulnerable to strong ground motion due to the location of shear walls along the transverse and longitudinal direction of the building [30]. It has been approved by Hamid [32] on the seismic performance of double unit TFB, followed by Anuar and Hamid [33] on single TFB. Later on, further study was carried out by comparing the seismic behavior between unrepaired and repaired single unit TFB under out-of-plane and in-plane lateral cyclic loading [34]. However, this chapter will be focused on the seismic performance of single unit tunnel form building (TFB) tested under in-plane lateral cyclic loading. Figure 6 shows the detailing and construction of single unit TFB which was tested under in-plane lateral cyclic loading only. Figure 6(a) shows the detailing drawing of reinforcement bars for the single unit TFB together with foundation beam. Figure 6(b) demonstrates the construction of three-storey single unit TFB in Heavy Structural Laboratory, Faculty of Civil Engineering, Universiti Teknologi MARA, Shah Alam, Selangor, Malaysia. Meanwhile, Figure 6(c) shows the specimen is ready for testing under in-plane lateral cyclic loading starting from ±0.01%, ±0.1%, ±0.25%, ±0.5% and ±0.75% drift.

(a) Detailing of single-unit TFB under in-plane loading. (b) Construction of one unit TFB on strong floor. (c) The painted specimen is ready to be tested.

Figure 6. The detailing and construction of one unit TFB in heavy structural laboratory

Table 2 shows the values of elastic stiffness and secant stiffness for single unit of tunnel form building system which had been tested under in-plane lateral cyclic loading. The elastic stiffness and secant stiffness for the first cycle is higher than the second cycle because more energy was required to push the TFB in the first cycle and thus, gave higher values of stiffness. Table 3 shows the values of displacement ductility (μΔ) for single unit TFB tested under in-plane lateral cyclic loading in pushing and pulling direction for the first and second cycle. The maximum displacement ductility is 1.14 for single unit TFB, this ductility does not capable to resist the earthquake loading either in moderate, and severe ground motion. Ductility is an important parameter to determine the survivability of the RC buildings under earthquake disasters

Table 2. Values of elastic stiffness ($K_{elastic}$) and secant stiffness (K_{secant}) for single unit TFB

Stiffness (kN/mm)	Pushing for first cycle	Pulling for first cycle	Pushing for second cycle	Pulling for second cycle
$K_{elastic}$	8.8	7.1	8	6.75
K_{secant}	1.08	1.66	0.72	1.60

Table 3. Displacement ductility (μ_Δ) of single unit TFB in pushing and pulling direction

Number of cycles	Direction	Ductility ($\mu\Delta$)
First cycle	Pushing	1.14
	Pulling	1.00
Second cycle	Pushing	1.00
	Pulling	1.00

Conclusions

The following conclusions can be drawn as follows:

1) Visual observation shows that many cracks were observed at wet joint between column and precast shear-key wall panel, exterior beam-column joint with corbels, wall-slab and wall-foundation joints when subjected to in-plane lateral cyclic loading.
2) Hysteresis loops (load versus displacement) are used to determine the lateral strength capacity, stiffness, ductility and equivalent viscous damping for precast buildings.
3) The elastic stiffness is higher than secant stiffness for single bay double-storey house, exterior beam-column joints with corbels and three-storey tunnel form buildings.
4) Displacement ductility for all the three specimens are less than 2 and to survive under earthquake attack, the ductility of the structure should be within the range from 3 to 6 as specified by the current seismic code of practice (EC8).
5) Percentage of equivalent viscous damping for the first cycle is higher than second cycle because more energy is required to resist the strength capacity at elastic region (first cycle) than in the inelastic region (second cycle).
6) Most of the failure mode occurred at the wall-beam joints, wall-foundation joints, beam-column joints, wall-slab joints and column-foundation joints where all the vertical loads and horizontal loads are meet at these points.
7) The overall performance of the sub-assemblage and super-assemblage of the structural components are merely depending on the amount of steels provided in transverse and longitudinal directions, proper detailing of reinforcement bars as specified by any current seismic code of practice, quality of workmanship at site and quality of the materials used during construction.
8) It can be concluded that single and double tunnel TFB with shear walls performed the best as compared to precast beam-column joint with corbel and precast shear-key wall panel.

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