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SEISMIC FRAGILITY OF CONFINED MASONRY BUILDINGS: A STUDY CASE OF TYPICAL HOUSE AND SCHOOL IN INDONESIA

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Abstract: *Confined masonry (CM) is a construction type that is widely used in Asia, South America, and part of Europe. Post-earthquake surveys reported that CM buildings have excellent performance under earthquake load, however, some also reported poor performance of these buildings, generally associated with poor construction workmanship and high level of irregularity. Despite being in the same building class, the difference in performance is significant due to the difference in construction practice in each area, caused by the diversity of climate, economy, culture, and social aspects. This highlights the importance of a study of building fragility with a context of local practice for accurate and reliable seismic risk assessment. In this study, two Indonesian single-story CM buildings- one typical house and one typical school building- are assessed for seismic performance. To account for the variability in workmanship, two levels of construction quality are considered. The first level is the 'guideline-based' construction, which follows the Indonesian guideline for this typology. The second level- the 'common practice'- refers to typical construction that does not strictly follow the guideline. Two major differences between these two types of construction are the level of confinement and brick quality. The global capacity of each building is estimated by combining the capacity of each wall, which is estimated by pushover analysis of 2D models of the walls using SAP2000 software. This capacity assessment strategy is first validated using single wall experimental reports, with specific reference to Indonesian 'common practice' construction, and then used to estimate the global capacity of the two case study buildings. Results of the analysis show that the 'guideline-based' construction has significantly higher capacity than the 'common practice' construction, by more than 200%. The paper further presents the fragility and performance assessment of these buildings against the local code.*

Introduction

Confined masonry (CM) is the construction type where the masonry wall is confined by the reinforced concrete (RC) elements. Although the CM construction appears similar to the RC frame system, their load carrying mechanisms are different. The concrete elements in RC frame structure usually have larger size and elaborate reinforcement detailing, while in CM, they are smaller, often the same as the wall width, with very minimal reinforcement. The main load carrying system in the former is the RC frame with stiffness added by the wall, meanwhile in the CM system, the masonry wall is the main lateral restraining system aided by the concrete confinement (Arya et al., 2013). Another clear difference is the construction method. Unlike the RC frame system, the masonry wall is installed first, followed by the columns and beams in the CM system. CM has evolved through informal process based on its advantage to resist earthquake load. CM buildings is adopted in Mediterranean Europe, Latin America, South and Southeast Asia and China over the past 50 years (Meli et al., 2011).

Confined masonry (CM) is a promising building construction type that is applicable in many areas considering its availability, economical aspect, and simple construction method (Meli, et al., 2011). CM tend to be tolerant to minor design and construction flaw, and material deficiencies, in the case that the building has regular floor plan and sufficient wall density. Past earthquake data

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shows that CM has better performance compared to unreinforced masonry (URM) and non-ductile RC infill structure (non-ductile RC) (Gupta & Singhal, 2020). However, confined masonry buildings also suffered damage, mainly associated with insufficient numbers of confinement in one or both directions, discontinuous tie-columns and beams, inadequate connections, and irregular building configuration (Meli et al., 2011).

Report from 1939 Chile earthquake (7.8 M, with Modified Mercalli Intensity (MMI) XI) suggested that 50% of inspected CM buildings survived without any damage while 60% of unreinforced masonry (URM) suffered partial or total collapse. Low-rise confined masonry performed very well in the 1985 Llolleo (7.5 Ms) and 2010 Maule earthquakes (8.8 Mw) (Meli et al., 2011) (Brzev, et al., 2010) (Astroza et al., 2012), with only a few of them having moderate damage. Similarly, most of all confined masonry building that has no significant irregularities survived the 2017 earthquake in Iran (Najafgholipour et al., 2022).

In the case of Indonesia, massive damage to unreinforced masonry buildings (mainly Dutch tradition style URM) was reported in 2006 Yogyakarta-Indonesia (6.4 Mw) earthquake, but most of CM building survived (Boen, 2006). The damage of CM building generally reported due to poor quality of materials (mortar, concrete), poor workmanship. After the 2018 Palu earthquake, heavy damage and collapse of a few confined masonry schools were reported, mainly due to similar reasons mentioned above, in addition to poorly confined heavy gables, poor reinforcement detailing and large spans.

Aim and Objective

The objective of this study is to evaluate the seismic capacity of one-story confined masonry buildings with the context typical construction in Indonesia. This study compares the capacity of ‘common-practice’ construction with the ‘guideline-based’ construction which follow the guideline from Indonesian Ministry of Public Works and Housing (Kemen PUPR). A case of typical house and school is evaluated in this study, where its performance is evaluated against the seismic demand applicable in Indonesia, according to the Indonesian National Standard (SNI).

Furthermore, fragility functions are derived for each case study building. Although Indonesia had developed detailed seismic hazard map SNI-1726-2019 (BSN, 2019), there is limited literature on the fragility functions, especially for the confined masonry typology that is widely used in the country. Hence, the development of fragility functions based on typical construction in Indonesia will contribute to the seismic risk assessment of many cities in the country that are prone to high seismic hazard.

Methodology

This paper adopts the analytical fragility assessment methodology of Global Earthquake Model (GEM) (D'Ayala, et al., 2015) using a pushover analysis with a numerical model. Pushover analysis is carried out on 2D models of CM walls in SAP2000 (CSI, 2022), considering a variety of typical opening configurations, from which capacity curves obtained. The model is first validated using an actual laboratory experiment of full-scale CM wall of ‘common practice’ construction in Indonesia reported by Wijaya et al. (2011). The global building capacity is then derived by superimposing the individual wall capacities. The performance of building is evaluated by N2 method (Fajfar & Fischinger, 1989), by comparing the global capacity curve to selected seismic demand spectrum. Finally, the fragility functions are obtained by selecting representative ground motions and using the fragility through capacity spectrum assessment (FRACAS) (Rossetto, et al., 2016). The flowchart of this study summarized in Figure 1.

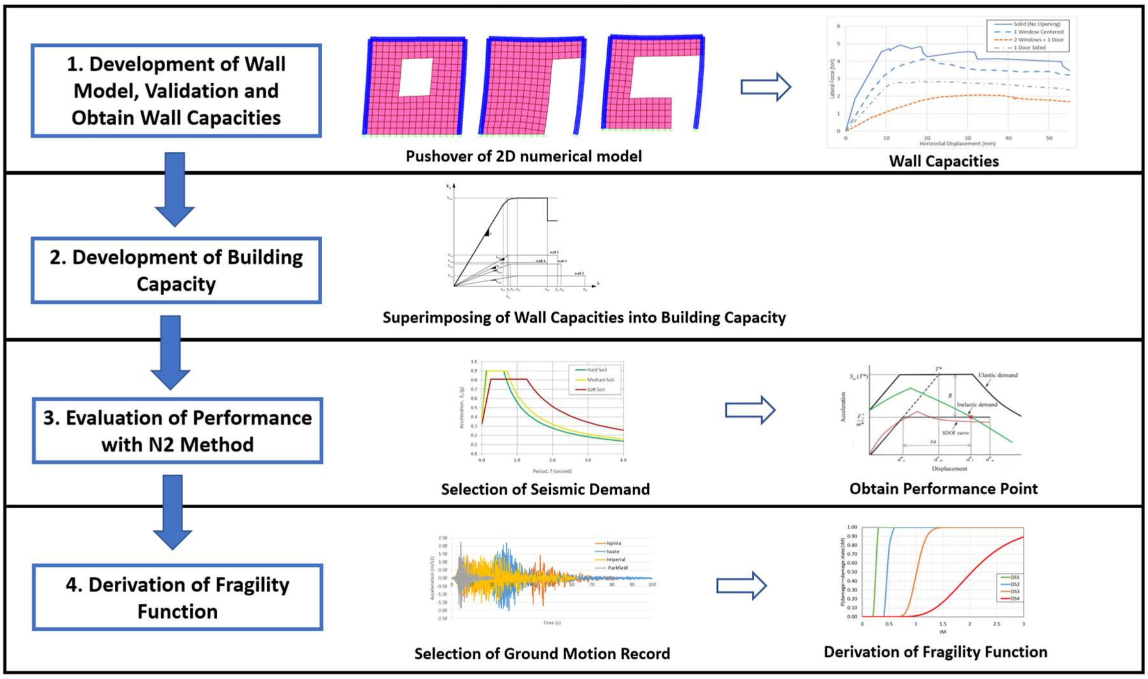

Figure 1. Flowchart

FEM Model

Existing approach to capacity analysis of CM building are using explicit finite element (EFE), applied element method (AEM) and Discrete Element (DEM). Depending on the discretisation level of element and the constitutive laws applied, the numerical approach for confined masonry can be categorized as micro element modelling, simplified element modelling and macro element modelling. By any method mentioned, numerical model of CM buildings is very complex that specific software and rigorous efforts is required (Vatteri & D’Ayala, 2021), (Adhikari & D’Ayala, 2020).

In this study, a confined wall model was constructed with the commercial software SAP2000 where the CM wall is modelled with non-linear shell element confined by frame element. By modifying the non-linear parameter, the capacity could be obtained to fit the reference capacity from the experiment. Compared to the existing approaches, this method is relatively simpler, however it has a limited application as it is unable to capture the complex behaviour of CM such as the separation of the brick and mortar, the crack development in the wall, and the separation between the wall and confining frame.

Construction of Building Capacity from Wall Capacity Curves

The building global capacity is obtained by superimposing the capacity of individual walls as described by (Lang, 2002).This approach assumes that the top floor or roof level is rigid so that all the walls have equal displacement, and only the walls in the strong axis (in-plane or IP) are carrying the shear force, while the contribution of the perpendicular (out-of-plane or OOP) walls are neglected. Thus, this is valid for relatively regular building where torsional effect is minimum.

The superimposition of the wall capacities can be written as:

$$V_b(\Delta) = \sum_j V_j(\Delta) \tag{1}$$

where:

Vb (Δ) = Capacity curve of building
Vj (Δ) = Capacity curve of wall, where j is the wall index

Performance Threshold

Several performance thresholds corresponding to both in-plane (IP) and out-of-plane (OOP) behaviour of CM walls and buildings have been summarized and it shows disparity in drift value for the same performance level (Parammal Vatteri & D’Ayala, 2021). For maximum reliability in the derivation of fragility functions, performance threshold used in this study are adopted from the experiments (Gumilang & Rusli, 2021; Wijaya, et al., 2011) that were used in the validation process. It is noted that the 'common practice' experiment utilized moderate quality brick while the 'guideline-based' experiment used high quality brick. In this study the drift threshold is hence divided into two categories: 1. for low-moderate quality of construction and 2. for high quality construction. The damage description is adopted from the 3D full-scale experiment of CM building (Zavala, et al., 2019). Table 1 summarizes the thresholds used in this study.

Damage State	**Performance Level**	**Description**	**Drift Threshold (%) (Low-Moderate Construction)**	**Drift Threshold (%) (High Quality Construction)**
DS1: Slight Damage	Operational	crack more than 1 mm opening started visible in the wall and confining frame	0.10%	0.10%
DS2: Moderate Damage	Life Safe	crack opening 2-4 mm, crack on confining element start to be notorious	0.25%	0.25%
DS3: Heavy Damage	Near Collapse	crack opening larger than 6-9 mm, windows and doors started to be broken	0.5%	0.75%
DS4: Complete Damage	Collapse	crack opening larger than 10 mm, strong deterioration in walls and confined elements, with doors and windows impossible to use	1.00%	1.5%

Table 1 Damage Thresholds for CM walls (Zavala, et al., 2019)

Layout of the Case Study Building 1

A typical building layout referred from Indonesian guideline, Permen PUPR 5/2016 (Kemen PUPR RI, 2016), is taken. The type-36 prototype (referring to floor area of 36 m^2) is a one-story residential building consisting of two bedrooms. The total weight of the house including the walls, confining elements and the flexible roof is 25 tonnes. The evaluation is carried out in its weakest axis, considering the number and area of walls. From the layout Figure 2 the X direction is weaker as it has lesser wall area.

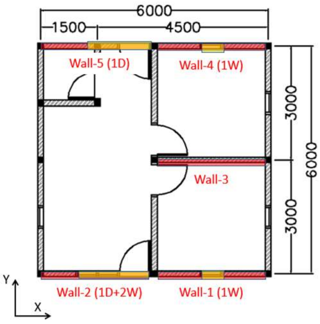

Figure 2 Layout of Type-36 House (Permen PUPR 5/2016)

Layout of the Case Study Building 2

Figure 3 shows the typical layout of classroom building in Indonesia, where a school will have several classroom buildings (YSTC, 2019). The layout shows that the walls at the front and back have openings along the wall, while the walls on the sides are solid without any opening.

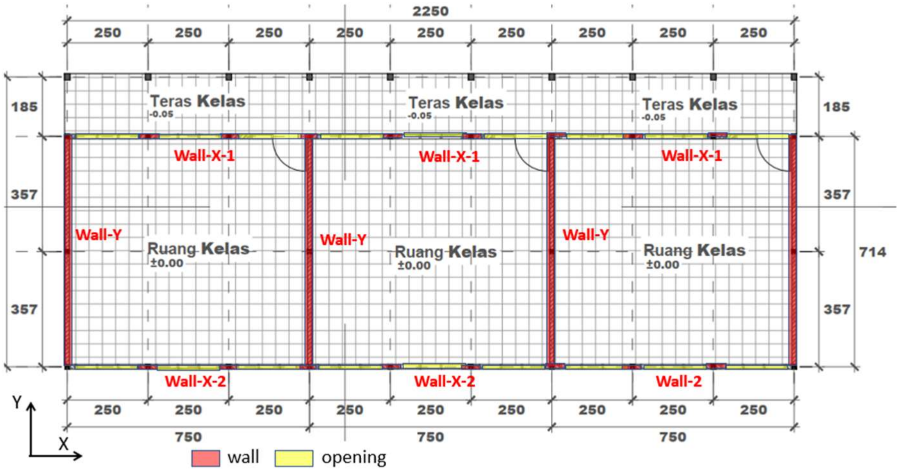

Figure 3 Layout of Typical one-story School Classroom Building (YSTC, 2019)

Construction Quality

Two levels of construction quality are considered. First is the 'common practice' construction which follow the actual construction practice in Indonesia reflected in the materials, reinforcement assembly, concreting and brick laying which a CM wall panel were tested experimentally by (Wijaya, et al., 2011). Second is the 'guideline based' construction which follow the Permen PUPR 5/2016 guideline (Kemen PUPR RI, 2016) where a full-scale 3D specimen was tested (Wijaya, et al., 2011). Two major differences between these two types of construction are the level of confinement and brick quality as provided in Table 2

Reference	**Wijaya et al. (2011)**	**Gumilang & Rusli (2021)**
Construction Basis	**Common Practice**	**PUPR 5/2016 Guideline**
Material Specification		
Concrete Comp. Strength	18 Mpa	19 Mpa
Brick Comp. Strength	3.5 Mpa	3.84 Mpa
Yield of Reinforcement	320 MPa	335 Mpa
Confining Element		
Column Size	150 x 150 mm2	150 x 150 mm2
Column Reinforcement	4 - φ10	4 - φ10
Column Confinement	φ8 - 200	φ8 - 150
Ring Beam Size	150 x 150 mm2	150 x 120 mm2
Ring Beam Reinforcement	4 - φ10	4 - φ10
Ring Beam Confinement	φ8 - 200	φ8 - 150
Masonry		
Brick Material	Clay Brick (Common)	Clay Brick (High)
Brick Dimension	55 x 100 x 205	50 x 110 x 200
Mortar	1:2:3 /	1:2:3 /
Plaster	No	20 mm
Plaster Specification	N/A	1:4 / cement:sand

Table 2 Material Specification

Analysis

Model Validation: In-Plane Direction

A validation of the numerical model was performed to ensure that the model is reliable to be used for the study. The validation of the model is carried out in reference to the laboratory test conducted by Wijaya et al., (2011), where a full scale 3 m x 3 m, 'common-practice' confined masonry wall specimen was tested under cyclic in-plane lateral loading. The construction of the specimens was according to common construction practice in Indonesia, including the reinforcement, concrete, and brick laying method.

A model in SAP2000 was constructed where the masonry element is modelled with layered shell element. It is found that the non-linear layered shell is the best to model the non-linear behaviour of CM wall where strength degradation occurs. While the degradation of masonry wall occurs through the shear failure and cracks in the mortar and brick element, in this case the degradation was modelled through yielding and degradation of layers in shell element.

The pushover load pattern is applied as acceleration in the opposite direction. This approach for loading is suitable for masonry buildings, especially if they have flexible roofs, as the seismic weight dominantly comes from the wall self-weight and not concentrated at the roof level.

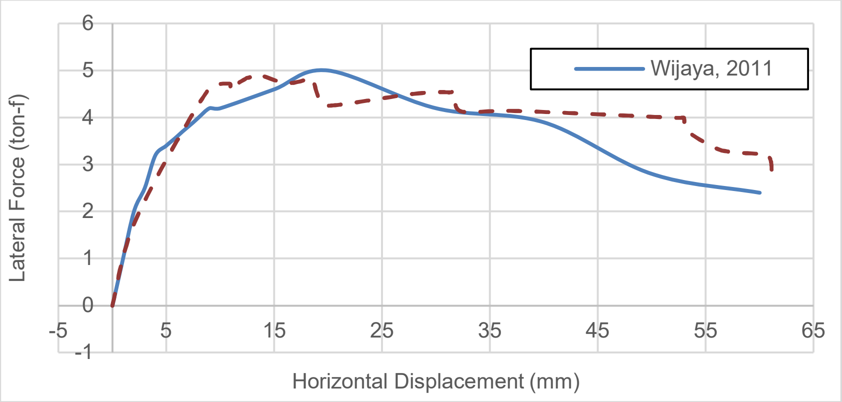

Figure 4 Validation of Model Capacity with Experiment by (Wijaya, et al., 2011)

Figure 4 shows that the model could capture the overall behaviour of the wall close to the experimental result. The initial stiffness and the degradation have similar trends, with difference less than 3%, even though there are some noticeable differences of peak point and at the non-linear phase. The energy dissipation, calculated as the area under the pushover capacity curve, is within a difference of 5%.

Effect of Opening

Opening is a common feature of every building. With tropical climate, Indonesian houses and buildings feature large windows, doors and ventilation in many sides. It is important to consider the effect of opening as it reduces the shear capacity of the CM wall panel. Effect of opening to lateral capacity had been studied in experiment of full-scale model by (Eshghi & Pourazin, 2009). It is reported that the typical central window opening reduce the initial stiffness by 40% and ratio of peak lateral load by 35%. Another laboratory experiment by (Okail, et al., 2016) shows window opening reduces the maximal lateral force capacity by 40%.

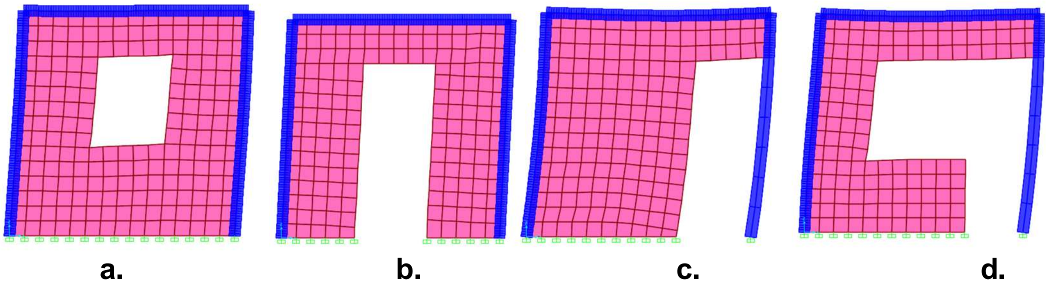

Figure 5 Deflection in SAP2000 Model: a. Central Window, b. Central Door, c. Side Door d. Side Door and Window

The effect of opening was explored in this study by modifying the SAP2000 model by removing the shell elements to represent the openings. Although this model is a simplified model that does not model the complex behaviour of CM such as the separation of the brick and mortar, the crack development in the walls, and the separation between the wall and confining frame, this model can be used to estimate the effect of opening to lateral capacity. Several type of opening (Figure 5) that typically featured in Indonesian buildings are modelled. The result of pushover capacity summarized in Figure 6.

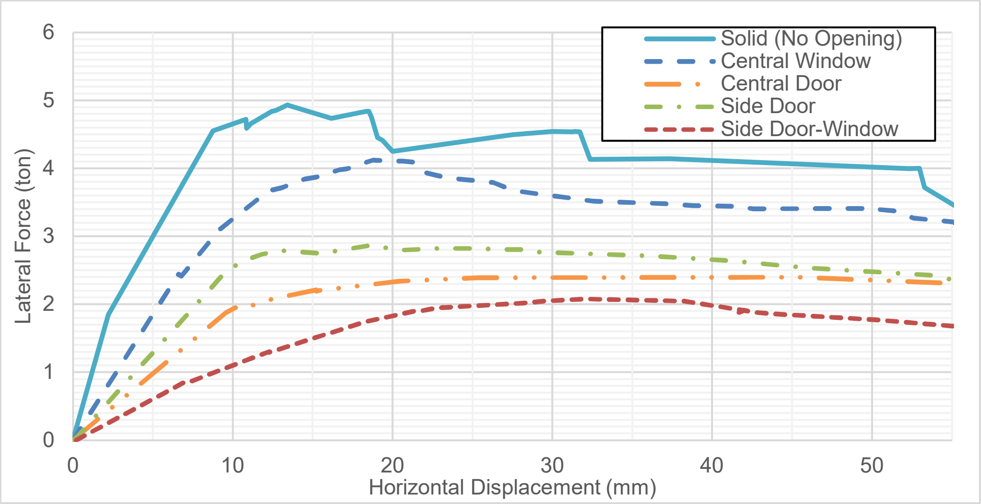

Figure 6 Capacity of Single Wall with Variation of Opening

Result

Capacity of Type-36 house (Common Practice vs Guideline Based)

Figure 7 shows that the capacity of the guideline-based building is higher by 160% than the common-practice construction. The capacity of 'common practice' is a conservative approach neglecting the contribution of out-of-plane walls, while the 'PUPR Guideline Based' capacity is the capacity of a real full-scale building which considers all the wall contributions. However, the increase of capacity if still very significant, with maximum lateral force more than two times. Interestingly, this significant increased occurs despite similarities of both building.

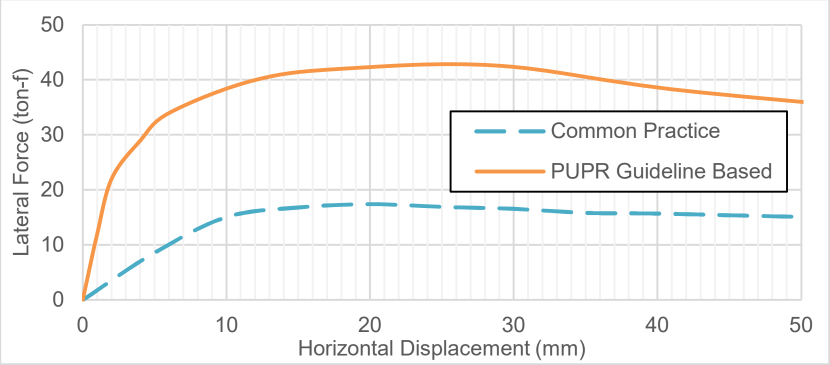

Figure 7 Comparison of Type-36 Building: Common Practice vs PUPR Guideline Based

Seismic Performance Assessment against the Local Code

The seismic demand used in this study is based on the Indonesian seismic standard, SNI-1726-2019 (BSN, 2019). This standard provides the map of spectral acceleration and formula to construct the demand response spectrum. The hazard considered is based on the probability of exceedance of 2% in 50 years, equal to the earthquake with return period of 2475 years. In this study, Palu is selected as the location of study which has various site classes identified, including hard soil (SC), medium soil (SD) and soft soil (SE) (Rusydi, et al., 2018). The response spectrum for those site classes are shown in Figure 8.

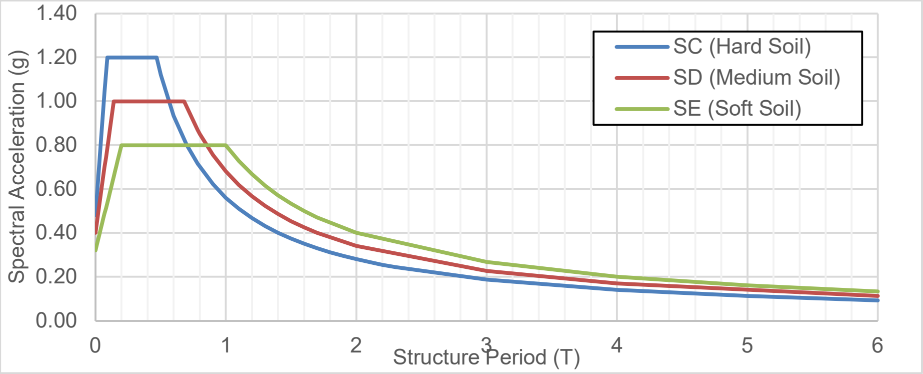

Figure 8 Response Spectrum Demand of Palu (SNI-1726-2019) for Various Site Class

The performance of the Type-36 and school buildings are assessed against the demand from SNI-1726-2019 and the results are shown in Table 3 and Table 4.

Type	**SC (Hard Soil)**		**SD (Medium Soil)**		**SE (Soft Soil)**	
	Performance	**Drift Demand (%)**	**Performance**	**Drift Demand (%)**	**Performance**	**Drift Demand (%)**
Common Practice	Moderate Damage	0.37%	Moderate Damage	0.45%	Heavy Damage	0.67%
Guideline Based	Slight Damage	0.16%	Slight Damage	0.15%	Slight Damage	0.12%

Table 3 Performance of Type-36 Buildings under SNI-1726-2019 demand

Site Class	**SC (Hard Soil)**		**SD (Medium Soil)**		**SE (Soft Soil)**	
Construction	**Performance**	**Drift Demand (%)**	**Performance**	**Drift Demand (%)**	**Performance**	**Drift Demand (%)**
Common Practice	Heavy Damage	0.60%	Heavy Damage	0.73%	Heavy Damage	0.83%

Table 4 Performance of Typical School Buildings under SNI-1726-2019 demand

This result shows that the type-36 house built with guideline-based construction has excellent performance compared to the 'common practice' building. By following the guideline, the drift demand reduced to less than 50%. In the other hand, the school building which assumed to be a 'common practice' construction suffered more damage compared to the type-36 house, with the drift is higher in average by 50%.

Fragility Function

The derivation of fragility curve of building in this study using the approach named FRACAS (Fragility through Capacity spectrum Assessment) developed by (Rossetto, et al., 2016). FRACAS use the capacity spectrum assessment method and uses inelastic response spectrum from earthquake ground motion records to construct fragility curve. Ground motions are selected based the seismicity character of Palu. PEER Ground Motion Database, PEER NGA-West2 Database (Ancheta, et al., 2013), is taken as the database source to select the representative ground motion. The fragility functions for each case derived by FRACAS are shown in Figure 9, Figure 10, and Figure 11.

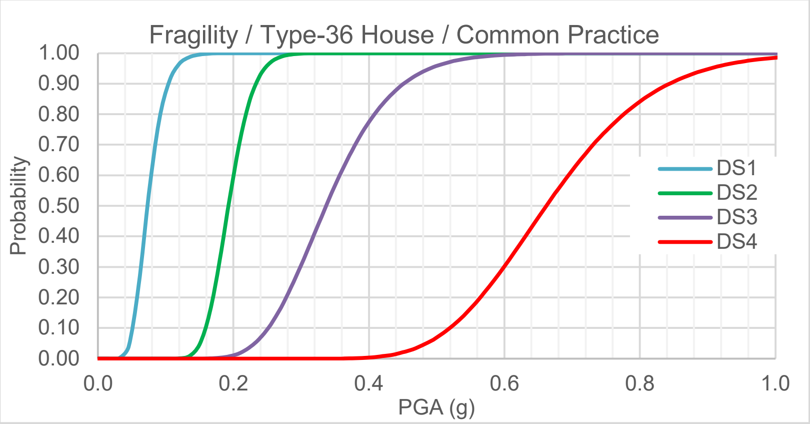

Figure 9 Fragility Curve of Type-36 House with 'Common Practice' Construction (IM=PGA)

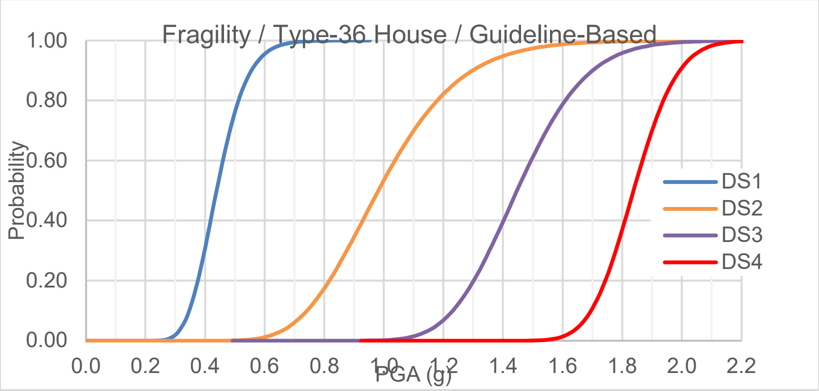

Figure 10 Fragility Curve of Type-36 House with 'Guideline-Based' Construction (IM=PGA)

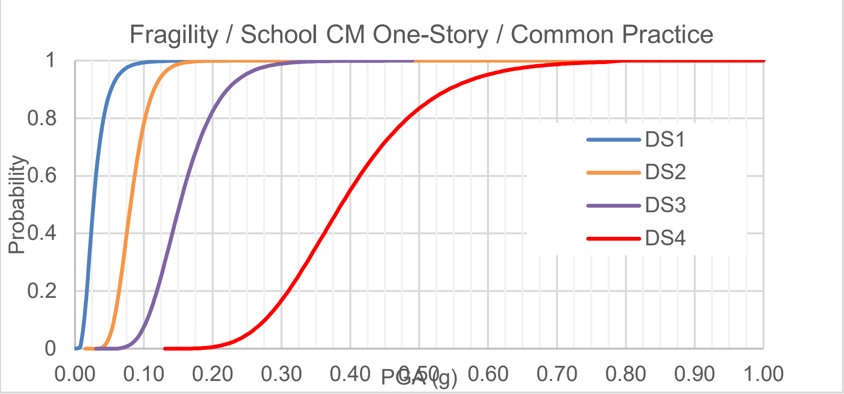

Figure 11 Fragility Curve of One-Story CM School Building (IM=PGA)

For the type-36 house, the median PGA corresponding to 50% probability of exceedance of DS3 is 0.32g for 'common practice' construction and 1.45g for 'guideline-based construction' providing the difference of 4.5 times. For the 'common practice' school building, the median PGA for DS3 is 0.15g which is half of same construction of the type-36 house.

Concluding Remark

1. This study shows that the detailing of the CM construction gives significant impact to the seismic capacity of the building. Despite very similar construction but difference in brick quality and stirrup spacing resulting in significant differences (160%) in seismic capacity.
2. The school building is more fragile than the type-36 house due to the layout in which classrooms are featured with long walls and continuous openings. This also causes the weak capacity along the walls with opening compared to the transversal direction with no opening.

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