17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

Comparative Analysis of Retrofitting Strategies to Reduce Seismic Loss of School Facilities

D. D'Ayala (1), A. Nassirpour (2), C. Galasso (3)

(1) *Professor, EPICentre, University College London (UCL), UK, d.dayala@ucl.ac.uk*
(2) *Teaching Fellow, EPICentre, University College London (UCL), UK, a.nassirpour@ucl.ac.uk*
(3) *Associate Professor, EPICentre, University College London (UCL), UK, and Scuola Universitaria Superiore (IUSS) Pavia, Italy, c.galasso@ucl.ac.uk*

Abstract

Philippines is frequently affected by disastrous seismic events, causing loss of lives and costly damage to the country's infrastructure. Educational facilities are often among the most exposed and vulnerable assets, requiring special attention in terms of seismic risk assessment and prioritisation of disaster risk reduction and resilience-increasing strategies (e.g. structural retrofit).

To this aim, this study investigates various retrofitting measures for vulnerable school buildings in the Philippines. Specifically, the study first investigates the seismic performance of three index buildings representing typical existing school building typologies in the country. The index buildings include two single-storey buildings, designed according to low- and moderate- seismic code provisions respectively, as well as a 3-storey building, design based on moderate seismic code provisions. The seismic performance of those structures is assessed through nonlinear static and dynamic analysis, identifying the structural deficiencies and proposing a number of retrofitting options to improve their overall capacity, stiffness and ductility. Reinforced Concrete Jacketing (RCJ) and Buckling Restrained Bracing (BRB) are considered as feasible retrofitting methods. The extent of performance enhancement is assessed through the capacity spectrum method as well as derivation of numerical seismic fragility and vulnerability relationships for various structure-specific damage states.

Results from the study indicated that in both cases (RCJ and BRB), the seismic performance of all three index buildings in terms of overall capacity and stiffness improves considerably. A comparison in terms of vulnerability relationships indicates that for the low-rise building with low seismic design, RCJ is the most efficient retrofitting method across a range of hazard intensity levels and will protect the building from weak column-strong beam mechanisms. For the low-rise building designed with moderate seismic loading, RCJ performs better. For the mid-rise index building with moderate seismic design, both methods of RCJ and BRB resulted in similar performance improvements and, hence, the selection of the optimal strategy should also be based on local availability, required design and implementation skills as well as economic constraints (e.g., installation costs).

Findings from this study can support local authorities and various decision-makers in prioritizing and allocating resources for strengthening plans of the most vulnerable school structures.

Keywords: Seismic Resilience; Retrofitting; School Infrastructure; Fragility Analysis; Vulnerability Assessment; IDA

1. Introduction

Educational facilities design/built prior to adequate building codes feature structural deficiencies common to other buildings of the same structural typologies in the same setting. However, several considerations set schools apart from other buildings in terms of priority for vulnerability assessment and retrofitting. An unsafe school in a natural-hazard-prone region can result in loss of life for hundreds of school children - a vulnerable population due to their age and their developmental stage - in addition to the potential damage to the property and education interruption. On the other hand, a safer and resilient school represents a safe haven for the local community, can serve as a temporary shelter in the immediate post-event and help to bring normalcy back to society in times of disaster. The collapse of a school building is particularly devastating to communities, as schools hold a community's future generation.

A review of multi-hazard vulnerability assessment reports of public-school buildings and possible resilience-increasing strategies, particularly in several developing countries, highlights several issues and shows a grim situation [1]. This is especially true for the Philippines, one of the most hazard-prone countries in the world. It is regularly subject to various disastrous natural events, inflicting loss of lives and costly damage to the country's infrastructure. In fact, the Philippines straddles a region of complex tectonics at the intersection of three major tectonic plates (the Philippine Sea, Sunda and Eurasia plates). As such, the country is exposed to frequent, large and damaging earthquakes. For instance, the M 7.2 Bohol earthquake in 2013, damaged more than 73,000 structures, of which more than 14,500 were totally destroyed, including several schools. According to the United Nations International Children's Emergency Fund (UNICEF), about 25,000 pre-schoolers and 275,855 school children in 1,200 early learning centres and 1,092 schools (931 elementary schools and 161 high schools) were affected by the earthquake. The recent history of reported damage and destruction indicates the substantial vulnerability of the country's infrastructure, particularly educational facilities, to seismic hazard. From the structural and architectural points of view, schools are especially vulnerable given structural characteristics that typically include large rooms, large windows (particularly in tropical climates), and corridors, all of which lead to lower stiffness that results in large lateral displacements of the structure during a major earthquake. Considering the large number of existing educational facilities and their geographical distribution in the country, appropriate analysis methods as well as recommendations for strengthening and retrofitting measures are especially needed to address the prevailing vulnerabilities of the existing school infrastructure.

Based on this remark, this study attempts to investigate the seismic performance of school infrastructure in the Philippines and to propose feasible and cost-effective retrofitting options. A number of index buildings is first defined based on available databases of school building typologies and their distribution across the country. Access to detailed structural and architectural drawings of school buildings as well as local expertise represent a unique opportunity to realistically simulate the considered structures with high detail. By utilising global and local earthquake ground-motion records, the seismic performance of the selected index buildings is assessed through advanced nonlinear numerical simulations, allowing the identification of various structural deficiencies. To address those, the feasibility of two different retrofitting measures, Reinforced Concrete Jacketing (RCJ) and Buckling Restrained Bracing (BRB), is investigated. Analytical seismic fragility and vulnerability relationships are derived for both the 'as-built' and retrofitted structural configurations, considering various damage states. The latter are defined based on their implications to post-earthquake functionality, repairability and recovery, including slight, moderate, extensive and complete/collapse damage.

Findings from this study can support local authorities and various decision-makers in prioritizing and allocating resources for strengthening plans of the most vulnerable school structures.

2. School Building Inventory

In the first phase of this study, available databases have been analysed to define the most common topologies of school buildings exposed to various natural hazards in the Philippines. The main reference database is that of the Filipino Department of Education (DepEd) [2], providing information on the types of buildings named after the era or the organisation responsible for their design and/or construction (e.g. Marcos type, DepEd type, Army type), as well as the number of classrooms and dimensions. As this dataset is mainly used in practice as an inventory checklist, it lacks fundamental engineering-related information, such as type of lateral-load resisting system, roof type, diaphragm behaviour, and age of construction etc.

In order to enhance the dataset to perform vulnerability assessment, the general description of the various building typologies is extracted from the construction manual provided by DepEd [3], together with a visual inspection of school buildings conducted through Google Street View, as well as photos of real-case buildings of different typologies. Accordingly, the school structures in the Philippines can be categorised into two main types based on their construction material and lateral-load resisting system, as shown in Figure 1. It is clear that reinforced concrete (RC) framed structures with infills represent the highest share within the considered exposure (70%), followed by light steel frames (23%).

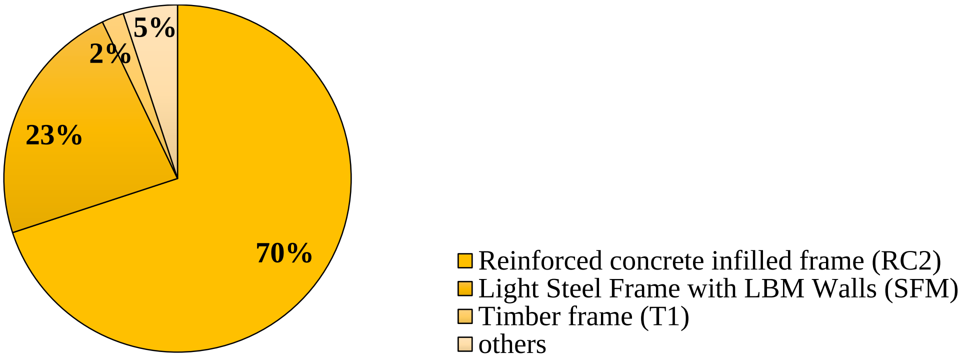

Figure 1 - Main construction material used in school buildings of Philippines

Among the considered parameters, the construction year of the building plays a critical role in the vulnerability assessment. Buildings of recent construction are more likely to be based on some hazard-informed design and feature ad-hoc seismic resistance details. Hence, it is expected that the vulnerability of recent buildings is lower compared to that of older building designed based on earlier building codes. To include these characteristics in the categorisation and identifying common school structures, the evolution of the structural design codes of the Philippines and the implementing regulations has been investigated as presented in Table 1. Additionally, the compliance of each code with the code levels in seismic design guidelines such as FEMA 356 [4] and HAZUS [5] has been considered in order to have a clearer view of their seismic resistance and vulnerability. It should be noted that any existing school, built pre-1970s in the Philippines has been considered as No-Code and such building need to be replaced, as they are highly vulnerable against seismic action.

Table 1 - Evolution of Philippine’s structural design codes and their compliance

Philippines Design Code (Edition)	Universal Building Code (UBC) Compliance	FEMA 356 & HAZUS Compliance
NBCP 1972 (1st edition; 2nd printing in 1977) National Building Code of the Philippines	UBC 1970	Pre-Code (PD)
NBCP 1982 (2nd edition)	UBC 1978	
NSCP 1987 (3rd edition) National Structural Code of the Philippines	UBC 1985	
NSCP 1992 (4th edition, Volume I – Buildings, Towers, and Other Vertical Structures; Volume II for Bridges published in 1997)	UBC 1988	Low Code (LD)
NSCP 2001 (5th edition, Volume I – Buildings, Towers, and Other Vertical Structures)	UBC 1997	Moderate Code (MD)
NSCP 2010 (6th edition, Volume I – Buildings, Towers, and Other Vertical Structures)	UBC 1997	
NSCP 2015 (7th edition, Volume I – Buildings, Towers, and Other Vertical Structures)	UBC 1997	

Combining the construction year, represented by the seismic design level and the main structural material and lateral-load resisting system used for construction, the considered school buildings have been categorised after the taxonomy proposed by D'Ayala et al. [6], as shown in Figure 2 and 3. Consequently, 35% of the infilled reinforced concrete buildings are classified as Moderate code (>2000), 10% are Low code (1990) and 23% can be categorised as Pre-code (1970-1990). Majority of masonry buildings are old, mainly built between 1960s and 1980s, and therefore are categorised as pre-code.

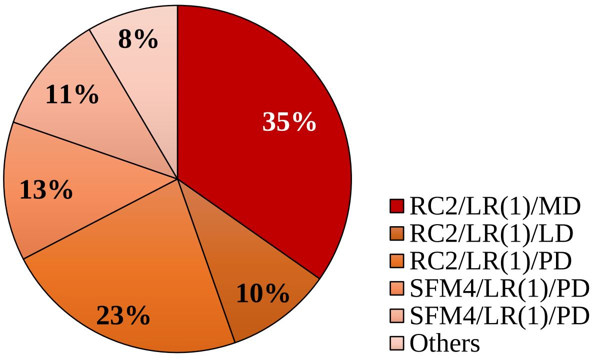

Figure 2 – Categorisation of building based on main structural material and design code

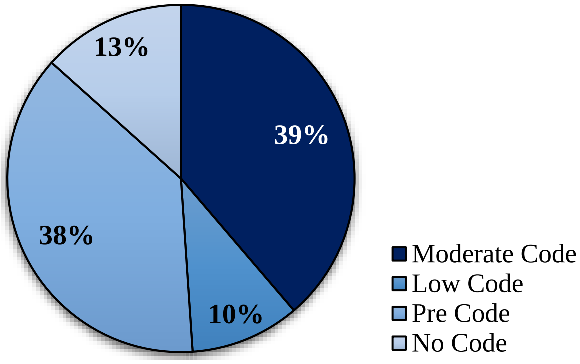

Figure 3 – Distribution of buildings based on the level of seismic code of the Philippines

Another important indicator of structural vulnerability against any natural hazard is the general height of the building. The dataset indicates that about 93% of the existing schools are single-storey buildings, while 6% are 2-storey building and only 1% have three or more stories.

The above observation clearly indicates that any index building should be representative of low-rise, single- or two-storey buildings (LR) with infilled reinforced concrete structure (RC2), built after 2000, following moderate seismic codes (MD).

3. Characteristics of the considered Index Buildings

Based on the results drawn from the previous section, three structures with the following characteristics have been defined as index buildings for this study.

A single storey, 5-classroom, RC frame with infills, designed according to the recent design code of the country, the National Structural Code of the Philippines (NSCP) 2010 (consistent with the UBC 1997), with moderate seismic resistance, (ID: RC2/LR(1)/MD) (Figure 4a). This index building mainly represents typical elementary schools with large classrooms (7.0×9.0 m^2), making the structure extremely flexible in both directions (low stiffness) and high potential for significant non-structural damage including the failure of infill walls (likely exceeding the operational limit state).

Furthermore, a similar one-storey infilled RC building is considered, which is designed following the NSCP 1992 (UBC 1988), indicating a lower ductility and seismic resistance, (ID: RC2/LR(1)/LD) (Figure 4b). The general characteristics and detailing of these two structural types are similar, for instance the column sections of both designs are 25×30 cm^2; however, the main variation is in the steel reinforcement detailing for both beams and column, which can lead to different failure mechanisms and most of the typical issue of pre-code buildings such as limited ductility, possible shear failure and strong beam–weak column phenomena.

Figure 4 – Single storey reinforced concrete, 5-classroom index buildings with various seismic design provisions a) RC2/LR(1)/MD, b) RC2/LR(1)/LD

The third index building is a three-storey, RC frame with infills, designed according to the more recent design code of the country, NSCP 2010 (UBC 1997), with moderate seismic resistance, (ID: RC2/MR(3)/MD) (Figure 5). Although the distribution percentage of three-storey or taller buildings is currently only 1%, majority of the future buildings built by DepEd will be multi-storey, particularly for secondary schools. Therefore, it is suggested that at least one index building should represent multi-storey buildings. The 15 classrooms are distributed over three storeys and include 12 bays and three frames (Figure 6). The spacing of bays and frames of all building are similar with classrooms having dimensions of 7.0×9.0 m^2 and storey heights of 3.2m. As discussed, the three-storey building has one of the largest footprints (≈ 1,540 m^2) among the typical school buildings in the Philippines. With an average of 45 students per classroom according to the DepEd database, the building accommodates more than 675 students and staff, making it particularly a high-risk case against ground shaking. It should be noted that the buildings do not include any staircase core or shear walls to result in significant torsional effects.

Figure 5 – 3D schematic view of the three-storey index building (RC2/MR(3)/MD)

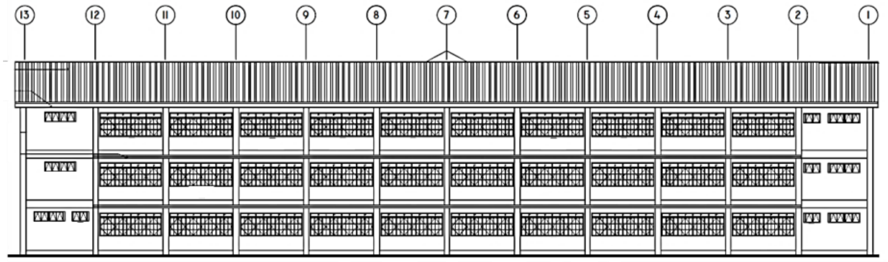

Figure 6 – 2D planar view of the three-storey index building (RC2/MR(3)/MD)

As the majority of the pre-code older buildings will be replaced with newly DepEd designed school buildings, the pre-code single-storey infilled RC frames (RC2/LR(1)/PD) will not be specifically considered and assessed in this study.

Detailed drawings for each of the considered school buildings are available; in this way, refined three-dimensional models of the school structures can be developed and analysed through numerical modelling. For the three considered buildings, various configurations in terms of number of bays (x-direction) and frames (y-direction), respectively 2 in 2, 5 in 2 and 10 in 2, have been initially defined. However, non-linear static analysis results in terms of capacity curves show similar seismic response in terms of both base shear coefficient and overall ductility. Therefore, only one arrangement has been modelled in detail for each of the defined index buildings.

4. Numerical Modelling & Seismic Analysis

Nonlinear models of the index buildings have been developed in OpenSees [7], using lumped plasticity. OpenSees is capable of predicting large displacements of the structure under static and dynamic loadings, taking into account both geometric non-linearities (e.g. P-Δ and P-δ) and material inelasticity. In this case, all columns and beams were assumed as elastic elements, while the non-linear behaviour was concentrated at the ends of structural components by implementing inelastic zero-length springs. The M-θ relationship was based on the hysteretic model proposed by Ibarra et al. [8], the IMK model. This model considers material degradation and pinching, as well as strength and stiffness deterioration in both unloading and reloading phases during each cycle. The main parameters of the IMK model were calibrated based on the empirical equations proposed by Haselton et al. [9].

In conventional seismic design, infill walls are usually considered non-structural elements and treated as additional mass on the structural elements. This might lead to great uncertainty in characterizing the seismic response during real earthquake events. In fact, infill walls tend to increase lateral stiffness and strength of the frame as well as improving energy dissipation capacity [10]. However, the presence of such infills can cause disruption to the distribution of seismic actions due to their inter-action with the structural RC frame. Their asymmetric distribution can also produce unfavourable failure mechanisms such as soft storeys as a result of the significant stiffness variation between the storeys. Based on these considered, it is quite important to account for their effects on the global behaviour to obtain reliable assessment of the seismic performance for the structure under consideration. In case of global structural response, it is preferable to implement more simplified models that allow capturing the overall behaviour efficiently and at the same time reduce the required computational effort, especially if numerous analysis is required. For this study, the infill walls were idealised as equivalent double diagonal struts, which are defined as truss elements with non-linear material properties in OpenSees. A uniaxial bilinear hysteretic model with pinching effect and stiffness degradation on the basis of ductility, proposed by Liberatore and Decanini [11] is implemented to replicate their behaviour.

Nonlinear static pushover analysis (SPO) has been conducted firt with incremental inverted triangular distribution, performed independently for both the longitudinal and transversal direction of each building. A response control is introduced to terminate the analysis once the control node, located at the roof’s centre of mass, reaches a drift of 0.3m.

The capacity of each column has been evaluated separately, in terms of axial, shear and flexural capacity, as well as the sufficiency of confinement according to the NSCP 2015 [12]. Referring to the Axial-Moment domains of the columns, results indicate that all ground floor columns of both index buildings lack sufficient flexural capacity and confinement, which can lead to soft-storey failure of the structure.

5. Proposed Retrofitting Measures

Two retrofitting techniques have been proposed in this study considering the material availability, local knowledge and labour skills. The considered strategies include Reinforced Concrete Jacketing (RCJ) and Buckling Restrained Bracing (BRB). RCJ can address deficiencies related to inadequate shear and flexural capacity, as well as enhancing the concrete compression strength and ultimate strain due to lack of confinement. BRB, can increase the structural stiffness and enhance the overall capacity of the building. In general, due to the positioning of wall partitions, ceilings and/or other architectural or structural elements, accessing structural members to apply RCJ and/or BRB is an inevitable challenge, possibly leading to disruption for the building. In particular, local removal of structural members, such as the slab, may be required, particularly in case of beam-column joints.

In both cases the target performance for the retrofit design has been defined as life safety of the occupants. To have a better understanding of whether the retrofitting is effective and to what extent the structural capacity and ductility have improved, the idealised SPO curve of each index building is plotted against the elastic and inelastic code response spectrum following the μ-R-T methodology. In this case, the inelastic response spectrum is derived in terms of the ductility factor (μ) and ductility reduction factors (R_{μ}), expressed as a function of structural period and the characteristic period of the ground motion (T_C). The characteristic period is defined as the transition period from the constant acceleration domain to the constant velocity domain of the elastic spectrum and depends on the frequency content of the ground motion. A comparison of the capacity curves obtained for the index building RC2-MR(3)-MD before and after retrofitting is illustrated in Figure 7. Four structure-specific damage limit states are also presented for better comparison of the achieved performance.

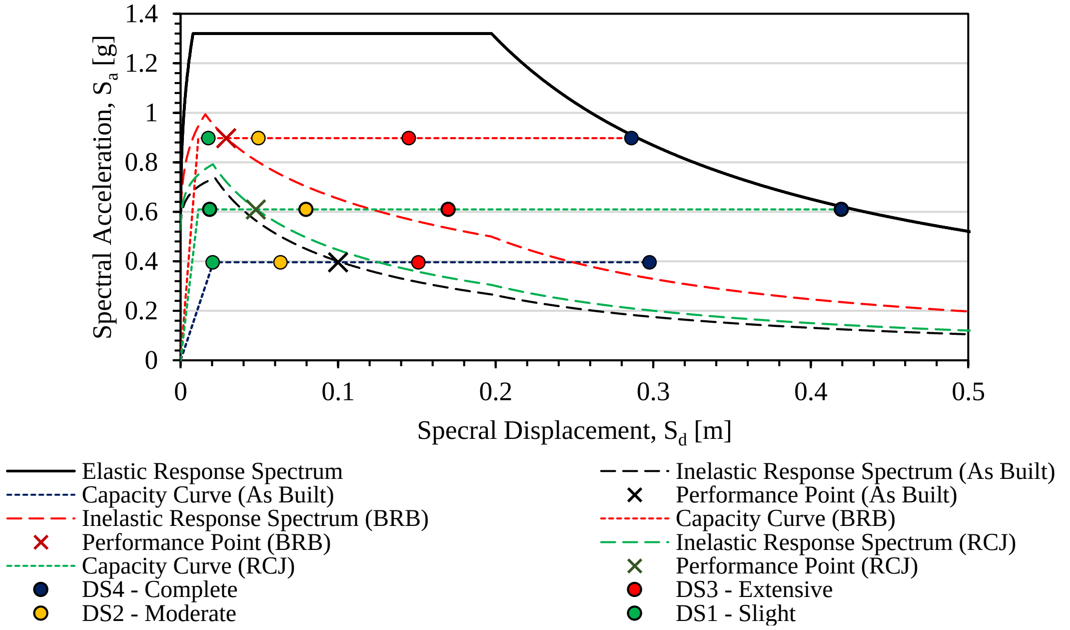

Figure 7 – Nonlinear static pushover capacity curve of the analysed index school building (RC2-MR(3)-MD) in S_a-S_d environment, before (As Built) and after retrofitting (RCJ and BRB)

Tables 2 to 4 indicate the characteristics of the three index buildings before and after the application of RCJ and BRB retrofitting techniques. Properties such as the ratio of reinforcement area to the gross area of section, link spacings in columns or number of added braces are presented. In case of RCJ, as expected, the dimensions of columns need to be increased, resulting is higher overall stiffness. In case of BRB, to have an optimum design and performance, several arrangements of bracing positioning and properties have been studied. The resultant stiffness after application of RCJ and BRB have been estimated, which can be used to indicate the extent of improvement. In the case of RC2-LR(1)-LD (i.e. low seismic design), tweak column–strong beam mechanisms were initially observed, which were addressed by introducing the RCJ and BRB.

Table 2 - Structural characteristics of As Built and Retrofitted (RCJ and BRB) for RC2-LR(1)-LD

	Storey	**Column Dimensions [m]**	**A_{stot} Column**	**$\rho = A_s/(BH)$**	**Links Spacing [mm]**	**Strong Column - Weak Beam**
As Built	1	0.25 × 0.25	4 B14	0.98	200	Not Verified
RCJ	**Storey**	**Column Dimensions [m]**	**A_{stot} Column**	**$\rho = A_s/(BH)$**	**Links Spacing [mm]**	**$K_{storey\ stiffness\ RCJ}$ / $K_{storey\ stiffness\ As\ Built}$**
	1	0.40 × 0.40	12 B14	1.15	75	2.85
BRB	**Storey**	**Column Dimensions [m]**	**No. of BRB**	**F_{ci} [kN]**	**K_{ci} [kN/m]**	**$K_{storey\ stiffness\ BRB}$ / $K_{storey\ stiffness\ As\ Built}$**
	1	0.35 × 0.40	2	234	213,388	3.39

Table 3 - Structural characteristics of As Built and Retrofitted (RCJ and BRB) for RC2-LR(1)-MD

	Storey	**Column Dimensions [m]**	**A_{stot} Column**	**$\rho = A_s/(BH)$**	**Links Spacing [mm]**	**Strong Column - Weak Beam**
As Built	1	0.20 × 0.30	4 B16	1.34	75	Verified
RCJ	**Storey**	**Column Dimensions [m]**	**A_{stot} Column**	**$\rho = A_s/(BH)$**	**Links Spacing [mm]**	**$K_{storey\ stiffness\ RCJ}$ / $K_{storey\ stiffness\ As\ Built}$**
	1	0.20 × 0.50	8 B16	1.61	75	2.31
BRB	**Storey**	**Column Dimensions [m]**	**No. of BRB**	**F_{ci} [kN]**	**K_{ci} [kN/m]**	**$K_{storey\ stiffness\ BRB}$ / $K_{storey\ stiffness\ As\ Built}$**
	1	0.20 × 0.30	2	168	139,228	2.00

Table 4 - Structural characteristics of As Built and Retrofitted (RCJ and BRB) for RC2-MR(3)-MD

	Storey	**Column Dimensions [m]**	**A_{stot} Column**	**$\rho = A_s/(BH)$**	**Links Spacing [mm]**	**Strong Column - Weak Beam**
As Built	1	0.35 × 0.40	12 B20	2.69	75	Verified
	2	0.35 × 0.35	12 B20	3.08	75	Verified
	3	0.35 × 0.35	8 B20	2.05	75	Verified
RCJ	**Storey**	**Column Dimensions [m]**	**A_{stot} Column**	**$\rho = A_s/(BH)$**	**Links Spacing [mm]**	**$K_{storey\ stiffness\ RCJ}$ / $K_{storey\ stiffness\ As\ Built}$**
	1	0.35 × 0.60	20 B20	2.99	75	1.79
	2	0.35 × 0.50	20 B20	3.59	75	1.64
	3	0.30 × 0.30	8 B20	2.05	75	1.00
BRB	**Storey**	**Column Dimensions [m]**	**No. of BRB**	**F_{ci} [kN]**	**K_{ci} [kN/m]**	**$K_{storey\ stiffness\ BRB}$ / $K_{storey\ stiffness\ As\ Built}$**
	1	0.35 × 0.40	4	919	267,075	1.77
	2	0.35 × 0.35	4	692	169,032	1.72
	3	0.35 × 0.35	3	259	109,801	1.35

Results of the numerical analysis show an increase in both strength and stiffness as the RCJ is applied to the selected columns. This is evident from the resultant capacity curve and the estimated stiffness ratio. As a result, the structure's ductility demand reduces, particularly in the case of the low-rise (1-storey), where due to the large bays and presence of slender members in plan, the frame was initially extremely flexible. Similarly, in the case of BRB, the structure became stiffer, hence reducing the maximum obtained displacement. This can be particularly useful in limiting the damage to non-structural elements such as the infills. The presence of BRBs raised the structural capacity considerably in comparison to the 'as built' configuration in all three index buildings.

6. Seismic Fragility & Vulnerability Analysis

Fragility functions are one of the fundamental tools in assessing seismic risk of structures, describing the probability of exceeding different damage limit states for a given level of ground shaking. Nonlinear Incremental Dynamic Analysis (IDA) on equivalent single degree of freedom system (SDoF) has been performed to obtain the performance points (i.e. intensity measure, IM, vs engineering demand parameter, EDP) and derive numerical fragility relationships. To this aim, eleven earthquake records have been selected from the PEER NGA-West2 dataset according to ASCE 7-10 provisions [13] and scaled to match the code response spectrum of Philippines [12] (Figure 8). The selected records have a moment magnitude (M_W) ranging from 6.20 to 7.62 with an average magnitude of 7.0 and all were recorded at sites located at a distance between 0.62 to 9.34 km from the fault rupture.

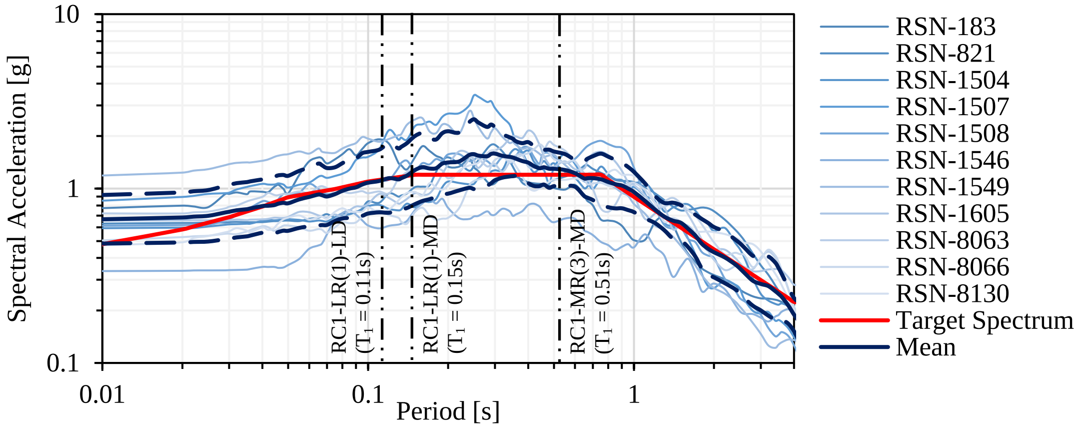

Figure 8 – Response spectra of even records matched to the code based elastic response spectrum (NSCP C101-10)

A critical stage in the fragility function derivation includes characterising appropriate damage states (DS) and allocating rational global and local damage thresholds. For the structures under study, maximum inter-storey drift ratio (MIDR) is employed as the EDP, a quantifiable global indicator for each damage state (Table 5). MIDR is a suitable choice for RC frames, since it relates the global response of the structure to joint rotations, in which most of the inelastic behaviour of RC frames is concentrated. Fragility functions in terms of peak ground acceleration (PGA), pseudo-spectral acceleration at the structure's fundamental period ($S_a(T_1)$) and $AvgS_a$ (range: $1.5T_1 – 2.0T_1$)(Figure 9) have been derived for all three index buildings before (As Built) and after retrofitting with RCJ and BRB.

Table 5 - Damage thresholds implemented in deriving fragility functions for as built and retrofitted index building

Damage State	**RC1-LR(1)-LD**			**RC1-LR(1)-MD**			**RC1-MR(3)-MD**		
	As Built	**RCJ**	**BRB**	**As Built**	**RCJ**	**BRB**	**As Built**	**RCJ**	**BRB**
DS1 - Slight	0.15%	0.20%	0.10%	0.30%	0.20%	0.20%	1.70%	2.50%	1.70%
DS2 - Moderate	0.65%	0.80%	0.65%	0.90%	0.90%	0.90%	4.90%	6.60%	3.90%
DS3 - Extensive	1.00%	1.80%	2.50%	2.50%	2.50%	2.50%	12.00%	12.00%	10.00%
DS4 - Complete	2.50%	3.00%	5.00%	6.00%	5.00%	5.00%	23.00%	23.00%	23.00%

The fundamental period (T_1) of the structures changes significantly as the retrofitting is applied, due to increase in mass and stiffness.

Vulnerability relationships are finally evaluated for each index building in the three considered situations, as built, retrofitted with RCJ and BRB (Figure 10). To derive the vulnerability relationships, damage ratios (DR) are needed for each of the damage states considered. For this study, values of 0.02, 0.10, 0.40 and 1.00 are considered as mean damage ratios for damages states from slight damage to complete respectively [14].

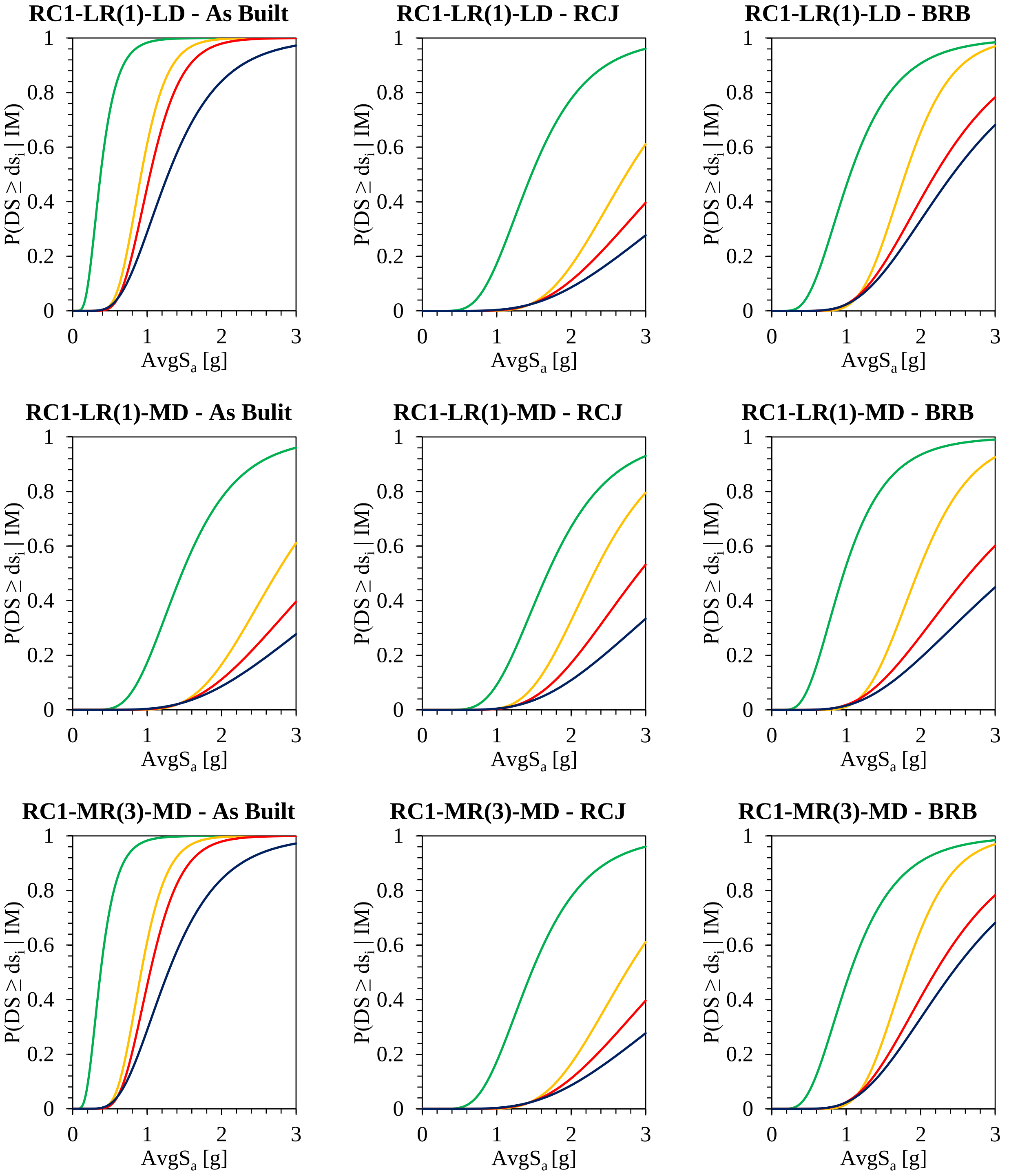

Figure 9 - Fragility curves derived for the index buildings before and after retrofitting with RCJ and BRB (Green: DS1 - Slight; Orange: DS2 - Moderate; Red: DS3 - Extensive; Dark Blue: DS4 - Complete)

The vulnerability curves clearly indicate that the considered retrofitting techniques can improve the performance of the buildings. In the case of RC1-LR(1)-LD, RCJ is clearly the most efficient retrofitting method. While, for RC1-LR(1)-MD, which is the most vulnerable structure, RCJ resulted in lower vulnerability at higher seismic intensities. Both RCJ and BRB have close vulnerability outcome in case of RC1-MR(3)-MD. The replacement cost of the considered school buildings is estimated to be around $450.00 per metre squared according to local sources and DepEd estimations.

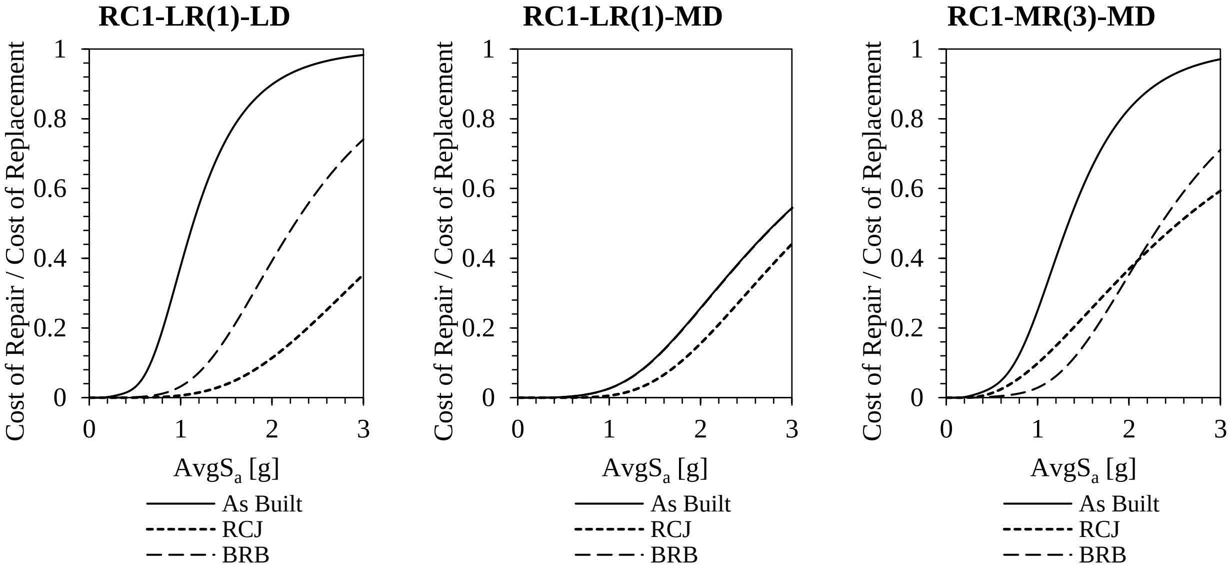

Figure 10 – Vulnerability curves obtained for the index buildings before and after retrofitting with RCJ and BRB

7. Conclusions

To analyse the seismic performance of the Philippine's school infrastructure, three index buildings have been selected based on the country's school database. Two single-storey RC framed structures with infills, with low and moderate seismic code designs have been selected as index building. Furthermore, a 3-storey RC frame with infills, designed with moderate seismic considerations is defined, representing the replacement option for aged school buildings.

Based on detailed drawings of the considered index buildings, detailed models of the structure have been developed using OpenSees. The seismic performance of the structures has been evaluated using nonlinear static pushover analysis (SPO), as well as incremental dynamic analysis (IDA) using various ground motions, spectrally matched to the Philippines code-based response spectrum. The analysis outcomes indicated deficiencies in structural capacity and ductility as well as potential for weak column–strong beams, leading to soft-storey failure at the ground floor of the index buildings. Therefore, two retrofitting methods, RCJ and BRB have been proposed, while considering the availability of material and local expertise.

The considered retrofitting measures have been applied with the aim to shift the seismic performance to life safety. As expected, the performance of all three index buildings improved considerably. The obtained vulnerability relationships indicates that in case of the building with low seismic design, RCJ is the most effective retrofitting method and will protect the building from weak column-strong beam phenomena. While, for the single-storey building designed based on moderate seismic design, RCJ is more effective than BRB. In the case of the 3-storey index building, both methods of RCJ and BRB can be equally effective. The final decision on selecting the best retrofitting option will then be dependent on the cost, availability and applicability.

This study is part of a wider research toward a more comprehensive framework on safer schools against natural disasters in the Philippines.

8. References

[1] GPDRR, (2009) Creating Linkages for a Safer Tomorrow, Global Platform for Disaster Risk Reduction, Proceedings: Second Session of the Global Platform for Disaster Risk Reduction.

[2] DepED (2017), DO 1, S. 2017 – Guidelines on the National Inventory of DepEd Public School Buildings for School Year 2016-2017., Department of Education, Department of Education, Pasig City, Philippines.

[3] DepED (2010), “Educational Facilities Manual, Revised Edition of the 2007 Handbook on Educational Facilities Integrating Disaster Risk Reduction in School Construction”, Physical Facilities and Schools’ Engineering Division, Office of Planning Service, Department of Education, Department of Education, Pasig City, Philippines.

[4] FEMA, (2000). FEMA-356: Pre-standard and Commentary for the Seismic Rehabilitation of Buildings. Rehabil. Requir. 1–518.

[5] HAZUS-MH MR4, 2003. HAZUS-MH MR4 Technical Manual. Natl. Inst. Build. Sci. Fed. Emerg. Manag. Agency (NIBS FEMA) 712.

[6] D'Ayala D, Galasso C, Nassirpour A, Adhikari RK, Yamin L, Fernandez R, Lo D, Garciano L, Oreta A. Resilient communities through safer schools. International Journal of Disaster Risk Reduction. 2019 Dec 14:101446.

[7] McKenna, F. and Fenves, G. (2001). "The OpenSees Command Language Manual: version 3.0," Pacific Earthquake Engineering Center, Univ. of Calif., Berkeley. (http://opensees.berkeley.edu).

[8] Ibarra, L.F., Medina, R.A. and Krawinkler, H., 2005. Hysteretic models that incorporate strength and stiffness deterioration. Earthquake engineering & structural dynamics, 34(12), pp.1489-1511.

[9] Goulet, C.A., Haselton, C.B., Mitrani‐Reiser, J., Beck, J.L., Deierlein, G.G., Porter, K.A. and Stewart, J.P., 2007. Evaluation of the seismic performance of a code‐conforming reinforced‐concrete frame building—from seismic hazard to collapse safety and economic losses. Earthquake Engineering & Structural Dynamics, 36(13), pp.1973-1997.

[10] Dolšek, M. and Fajfar, P., 2005. Simplified non‐linear seismic analysis of infilled reinforced concrete frames. Earthquake engineering & structural dynamics, 34(1), pp.49-66.

[11] Liberatore, L. and Decanini, L.D. (2011), “Effects of infills on the seismic response of high-rise RC buildings designed as bare according to Eurocode 8”, Ingegneria Sismica 3, 7-23.

[12] National Structural Code of the Philippines (NSCP) (2015). Buildings, Towers, And Other Vertical Structures, Vol. 1. 7th edition, Association of Structural Engineers of the Philippines, Inc.

[13] ASCE/SEI 7-10, (2013), “Minimum Design Loads for Buildings and Other Structures.”, American Society of Civil Engineers, Reston, VA.

[14] DiPasquale-Goretti (2008), “Vulnerabilità funzionale ed economica degli edifici residenziali colpiti dai recenti eventi sismici italiani (Di Pasquale; Goretti, 2001)” - X Congresso Nazionale “L’ingegneria Sismica in Italia”.