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INCREASING SEISMIC RESILIENCE OF PHILIPPINES' SCHOOL INFRASTRUCTURE THROUGH STRUCTURAL RETROFITTING

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ABSTRACT

Philippines is one of the most earthquake-prone countries in the world, regularly subjected to destructive seismic events, inflicting loss of lives and costly damage to the country's infrastructure. Educational facilities are often among the most exposed and vulnerable infrastructure, requiring special attention in terms of seismic risk assessment and prioritization for structural retrofitting and disaster risk reduction. Hence, this study first investigates the seismic performance of two index buildings representing typical existing schools in the Philippines. The selection of the two index buildings follows a recently conducted rapid visual survey in the region and the gathering of detailed structural drawings of typical schools. The results obtained through nonlinear static analysis of the modelled index buildings indicate the possibility of a soft storey mechanics at the ground floor of both structures. To mitigate the identified structural deficiencies and improve the overall seismic performance of the two case-study structures, a retrofitting measure is then proposed. Specifically, fibre reinforced polymer (FRP) wrapping is designed for all beams and columns following recent international provisions and state-of-the-art practice. Furthermore, the effect of FRP retrofitting on the seismic capacity of the selected structures is measured through derivation of fragility functions for various damage states. The results of the analysis indicate a considerable improvement in the overall seismic performance of each considered structural system, particularly as the structure enters its inelastic behaviour. This study represents the first step toward identifying the most technically feasible and economical mitigation strategy for the vulnerable schools in the Philippines.

Keywords: Fibre Reinforced Polymer (FRP); School Infrastructure; Retrofitting; Fragility Analysis

1. INTRODUCTION

Low- to lower middle-income countries are disproportionately affected by extreme weather and other natural hazards, including climate change, setting back progress on poverty alleviation and slowing long-term development. They are often the most exposed to hazards, have limited coping capacities and find it harder to recover. Among those countries, the Philippines is a top disaster hotspot worldwide. It is highly exposed to a wide range of natural hazards, including earthquakes, volcanic eruptions, and other geological hazards, as well as to typhoons and monsoon rains, all of which limit the country's sustainable development. Catastrophe risk modelling for the Philippines (AIR Worldwide, *personal communication*) has shown the country is expected to incur, on a long-term average basis, PhP206 billion (approximately US$4.6 billion) per year in damage to public and private assets due to earthquake-induced ground shaking, wind and precipitation induced by tropical cyclones, and precipitation induced by non-tropical cyclones (monsoons). This analysis has considered a 10,000-year catalogue of possible events to provide a more robust quantification of disaster risks than one based on short-term historical records. In particular, earthquake losses are higher than those from tropical cyclones for larger mean return periods of losses (greater than twenty-five to thirty years). Conversely, tropical cyclone losses are greater at smaller mean return periods of losses. This is primarily because tropical cyclones occur more frequently than earthquakes in the Philippines, but strong earthquakes typically cause higher losses than large tropical cyclones. These risks are driven, in large part, by unplanned or poorly planned

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urbanization and the resulting concentration of assets and people in hazardous areas. The increase in people, compounded by inadequate construction quality of the built environment, places several urban areas across the country particularly at risk for catastrophic economic and human losses.

For instance, the most recent largest earthquake, the M 7.2 Bohol earthquake (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.

Numerous evidence of previous events has highlighted the vulnerability of school infrastructure to natural hazards and particularly to earthquakes (e.g., Doroteo, 2015). 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. At the same time, schools play a critical role in the education of a community's next generation, with school children being one of the most vulnerable components of the society due to their age and their developmental stage (ASEAN, 2016). A safer and resilient school can save valuable lives of children, provide a safe haven for the local community, serving as a temporary shelter and helping to bring normalcy back to society in times of disaster. These considerations set school buildings apart from their peers in terms of priority for assessment and resource allocation for retrofitting/strengthening plans.

In this study, seismic vulnerability of school buildings is investigated through analytical fragility functions for various damage states. Two index buildings are selected following the statistical outcome of a rapid visual survey conducted on 115 school structures in Cagayan de Oro (CdeO), Philippines, as part of the recently completed SCOSSO project (Safer Communities through Safer Schools), funded by the UK Engineering and Physical Sciences Research Council (EPSRC) Global Challenges Research Fund (GCRF). Specifically, a 2- and a 3-storey reinforced concrete (RC) buildings are selected for this study. The selected index buildings are among the most common structures observed during the rapid visual surveying. Furthermore, the 2-storey building is the most likely option for replacing the older single storey school structures, while the 3-storey building has the largest footprint among the existing schools. Therefore, assessing the vulnerability of both buildings is of great interest for decision-making and disaster planning purposes.

Highly-detailed, finite element numerical models of the case-study schools are developed following the collected survey data, accessible detailed drawings, the local design provisions, and local practice. Through nonlinear static analysis of the developed three-dimensional computational models, the major structural deficiencies are identified, allowing the selection of the most feasible retrofitting measure. In this case, considering the ease and speed of application, required engineering skills, and the local availability, fibre reinforced polymer (FRP) is proposed for retrofitting the structures. Moreover, application of FRP retrofitting is less invasive in comparison to the more traditional measures such the concrete jacketing, resulting in less disruption to the schools' functionality, thus causing less education interruption. By simulating the effect of FRP on the global behaviour of the buildings and comparing the analytical fragility functions before and after the retrofitting, the efficiency of the selected retrofitting measure is quantified and discussed.

This study represents the first step toward identifying the most technically feasible and cost-effective mitigation strategies as part of a comprehensive framework to increase seismic resilience of the vulnerable school infrastructure in the Philippines.

2. RAPID SURVEYING OF SCHOOL INFRASTRUCTURE IN CAGAYAN DE ORO

A mobile application, SCOSSO App (freely available at the Android Play Store), has been utilized for surveying the school infrastructure of CdeO in Philippines (Nassirpour et al. 2018). CdeO is a highly-urbanized city, situated along the north central coast of the Mindanao island (8°29′N 124°39′E) and facing Macajalar Bay with 25 kilometres of coastline. According to the 2015 census, the city has a population of 675,950 and a density of 1,600/km^2, making it the 10th most populous city in the Philippines. The city is relatively close to some major seismic faults and it experienced the 2013 Bohol earthquake.

The mobile app allows one to collect general information on the building's geolocation and identification, structural characteristics and deficiencies. It also computes a multi-hazard vulnerability index (Nassirpour et al. 2018). The overall aim is to prioritize more detailed data collection campaigns and structural assessment procedures (e.g., analytical vulnerability approaches, through fragility and vulnerability relationships), and ultimately to plan further retrofitting/strengthening measures or, if necessary, school replacement/replacement.

A total of 115 school buildings were visually surveyed in four days, in September 2016. All the surveyed structures are in elementary grade campuses, across different locations of CdeO. A number of surveyed buildings are also designated as shelters in case of any disaster, and particularly floods and typhoons. In each school campus, a mixture of buildings, characterized by various construction years, materials, structural systems, and functions co-exists. As expected, a variation in the type of materials, workmanship and technology during the construction can also be observed, even in case of identical buildings. The structural type of the surveyed buildings ranges from masonry walls with timber roof to RC framed structures, with steel trusses supporting the roof. The typical number of storeys range between one to four, with a majority being single-storey, while a considerable proportion having two storeys (Figure 1). The plan shapes in most cases varied from regular square to rectangular plan with a few rare cases being L-shaped.

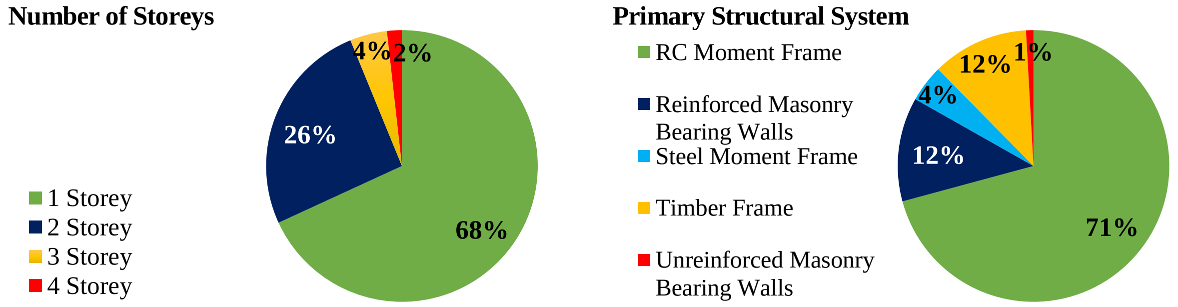

Figure 1. Statistics on number of storeys and primary structural systems of surveyed schools in Cayan de Oro – Philippines

Most of the surveyed buildings were constructed after 2010, while a considerable number were from the 1990s (Figure 2). As anticipated, signs of decay and poor structural conditions were observed in the structures which have been constructed over long periods of time.

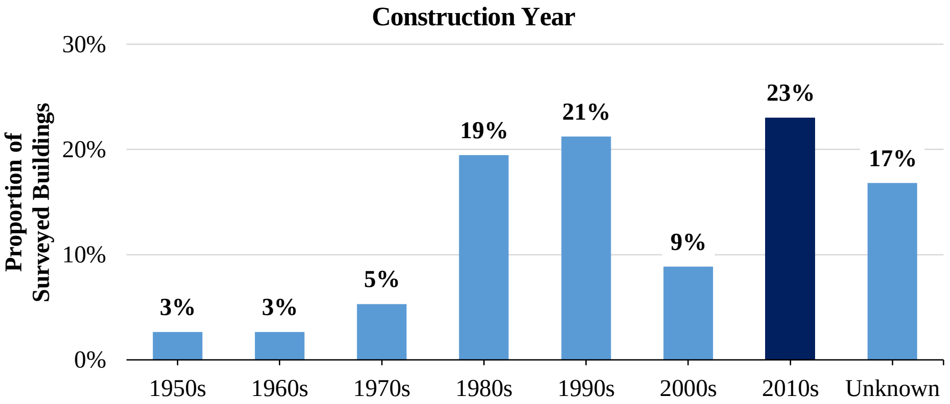

Figure 2. Statistics on construction year of surveyed schools in Cayan de Oro – Philippines

Among the buildings constructed after 2010, most of the buildings are RC framed structures and have two to three storeys. Furthermore, these building types are the main option for replacing the older school structures (Philippines Department of Education – DepEd - *personal communication*).

3. CHARACTERISTICS OF THE INDEX BUILDINGS

Based on the results of the rapid visual survey, two RC index buildings have finally been selected for this study. The first building is a 2-storey RC frame, consisting of two classrooms, one per storey, with two bays and three frames. The second structure includes 15 classrooms, distributed over three storeys, including 12 bays and three frames. The spacing of bays and frames of both building are similar with classrooms having dimensions of 7m × 9m. Storey height is 3.2m for each storey and each considered building. As mentioned earlier, the 3-storey building has one of the largest footprints (≈ 1,540 m^2) among the typical school buildings in the country. With an average of 45 students per classroom according to the survey observations, the building accommodates more than 675 students and teachers, making it a particularly exposed structure to ground shaking. The buildings do not include any staircase core or shear walls to result in significant torsional effects. Both structures are constructed post-2010. The plan and elevation of the selected index buildings are illustrated in Figure 3 and 4.

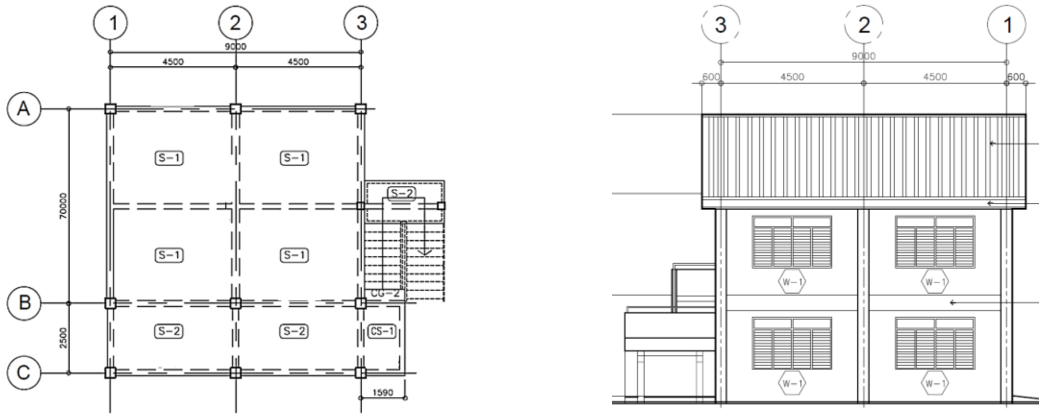

Figure 3. Plan (left) and elevation (right) view of the 2-storey, 2-classroom school (DepEd, 2012)

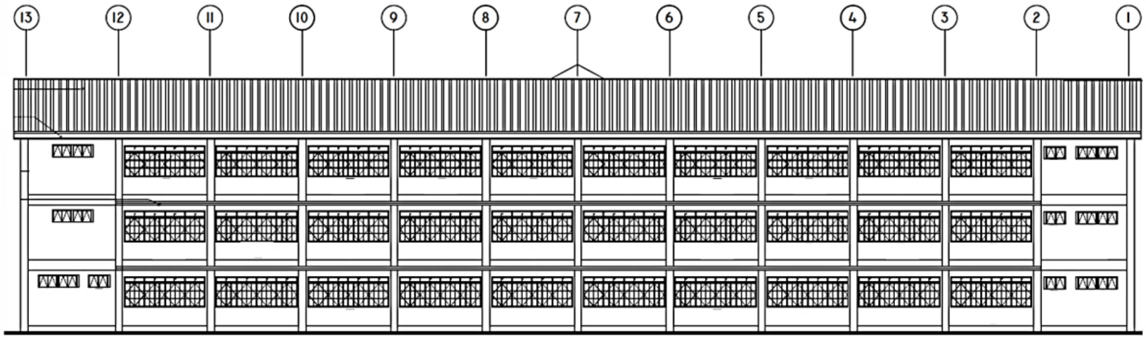

Figure 4. Elevation view of 3-storey, 15-classroom school (DepED, 2012)

As the elevation indicates, majority of walls and partitions consist of lightweight concrete hollow blocks (150 mm CHB) with relatively large openings as entrance doors or windows. Thus, the infill panels would not have a considerable effect on the global capacity and initial stiffness of the structures. Therefore, as a way of simplification, their effect is neglected in the numerical simulations. The unit weight of walls (1,040 kg/m^3) are added as distributed loading on the beams.

The material characteristics and section arrangements are defined following a statistical analysis of the schools' detailed drawing, made available by the DepEd, as well as the National Structural Code of the Philippines, Vol. 1 (NSCP, 2010). Accordingly, for beams, columns and slabs, a concrete with mean strength value of 28 MPa is implemented, reinforced with ribbed steel bars with a mean strength of 253 MPa. All members have 40 mm cover and have similar arrangement of longitudinal reinforcement. The shear bars are $\phi 10$ with spacing of 0.2 m.

An imposed load of 1.9 kPa for the classrooms and 3.8 kPa for the corridors are applied according to the NSCP (2010). The tributary area for the beams was assumed to follow a simplified triangular distribution, as the reinforcement arrangement in the slabs allows this load path to be achieved.

4. NUMERICAL MODELLING

Three dimensional nonlinear models of the index buildings are developed using the fibre-based finite element software SeismoStruct (2016). The software can predict large displacements of space frames under static and dynamic loadings, taking into consideration the geometric non-linearities (e.g. P-Δ and P-δ) and material inelasticity. It accounts for the spread of inelasticity along the members' length and across the sections' depth.

Reinforcing steel is modelled through a uniaxial bilinear stress-strain model with kinematic strain hardening; concrete is modelled using a uniaxial nonlinear constant confinement relationship proposed by Mander et al. (1988) and the cyclic rules proposed by Martinez-Rueda and Elnashai (1997). The slab modelling is carried out by implementing rigid diaphragms at each floor. Hence, a rigid slab is implicitly considered in the structural configuration, which is the case for the majority of RC buildings. The slab's loads are transformed to masses and applied directly to the beams that support the slab. Eigenvalue and static analysis are conducted to estimate the modal properties and the total mass of the structure as shown in Table 1.

Table 1. Modal properties of the selected models

Model Ref.	Mode	Period [s]	Frequency [Hertz]	U_x [tonne]	U_x [%]	U_y [tonne]	U_y [%]	R_z [tonne]	R_z [%]	Mass [tonne]
2-Storey, 2-Class	1	**0.21**	4.80	34.83	0.83	0.00	0.00	66.02	0.06	121.38
	2	0.19	5.34	0.00	0.00	37.92	0.91	0.00	0.00	
	3	0.18	5.68	2.37	0.06	0.00	0.00	892.75	0.84	
3-Storey, 15-Class	1	**0.51**	1.98	886.09	0.87	0.02	0.00	4651.28	0.02	1027.44
	2	0.49	2.03	0.03	0.00	905.94	0.88	20.39	0.00	
	3	0.46	2.19	17.34	0.02	0.09	0.00	235292.63	0.87	

As can see from Table 1, the influence of higher modes can be neglected, due to the rectangular configuration of the considered structures and the fact that more than 90% of the mass is excited by the first three significant modes for each considered direction (X and Y). As the overall structural behaviour is predominantly influenced by the first period of vibration and mode shape, nonlinear static pushover (SPO) procedure is a reliable mean of obtaining the structural response, which is also recommended by FEMA 273 (ATC-33, 1996). The SPO analysis can identify the structural weakness such as storey mechanisms, strength and stiffness irregularities along with extensive deformation demands, which cannot be acknowledged in an elastic analysis (e.g., Krawinkler and Seneviratna, 1998).

In this study, the SPO analysis is conducted with incremental uniform load distribution and an inverted triangular distribution, performed independently for both longitudinal and transversal direction of the building in order to identify the weaker direction. Response control is used to terminate the analysis once the control node, located at the roof's centre of mass, reaches a drift of 0.3 m (FEMA 356, 2000). The structural response, obtained in terms of base shear versus top displacement, will later be used to derive the fragility function through a simplified method. The outcome of the analyses on each building are presented in the next section.

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 National Structural Code of the Philippines, (NSCP, 2010). 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. Hence, retrofitting the beams and columns with FRP wrapping may improve the overall structural performance by increasing the structural capacity and, ductility through column confinement.

5. PROPOSED RETROFTTING MEASURES

In recent years, the application of FRP has risen in several earthquake-prone regions around the world due to their high strength to weight ratio, high elastic modulus, highly desirable mechanical properties, corrosion resistance and most notably its speed of implementation (e.g. De Lorenzis and Tepfers 2003; Wu et al. 2006). Several examples of FRP retrofitting for the school infrastructure has been observed in the post-2009 L'Aquila earthquake, Italy, for which FRP has been selected in a number of applications for its reduced installation time, allowing quick re-opening of the schools, while significantly increasing the seismic capacity of the building (Frascadore et al., 2015).

In general, FRP is considered expensive when compared to other retrofitting strategies such as concrete jacketing, steel bracing and the introduction of shear walls. However, the FRP wrapping is preferred in cases where there is limited access to the structure or minimal disruption is required (e.g., FEMA-547, 2006). FRP wrapping 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. To have a comprehensive cost comparison of FRP retrofitting techniques with the traditional methods of concrete or steel jacketing, different cost aspects should be considered, such as the cost of raw material, the need for specialized and experienced contractors, labour, equipment, quality control, temporary disruption, time of installation, and the permanent impact on the structural functions. Considering the importance of the project and the level of safety required, a simple cost-benefit assessment or a comprehensive life cycle cost analysis can identify the best retrofitting measure.

Depending on the case, due to the positioning of wall partitions, ceilings and/or other architectural or structural elements, accessing structural members to apply the FRP wrapping may be challenging. Therefore, local removal of structural members, such as the slab, may be required, particularly in case of beam-column joints. Furthermore, the potential slab interaction with the retrofitted member has to be considered in the design and analysis stage, as this may affect the strengthening requirements (e.g., FEMA-547, 2006).

For this study, the main aim is to increase the ductility and member strength following the observations of the nonlinear analysis. Referring to the structural analysis, the weakest beams and columns are identified and the FRP wrapping is designed accordingly to the guidelines of CNR-DT 200.1R-13 (CNR, 2014), while following the preferred strength hierarchy of strong column-weak beam (ASCE 41-13, 2013). This study implements the CNR as those guidelines are less conservative in comparison to the ACI 440 (2015), with the latter having a better overlay with the Philippines' design code, mainly based on the UBS (1997) (D'Antino & Pellegrino, 2013). As the retrofitting is implemented, the formation of plastic hinges on the columns is avoided with plastic hinges enforced at the beam end-points, as per concept of capacity design (e.g., NSCP, 2010). Furthermore, the design explicitly incorporated the optimal bond length, efficiency of confinement and orientation of fibres. The chosen FRP for all beams and columns is the commercial SikaWrap Hex 103C, selected based on availability in the region under study. The material properties of are presented in Table 2.

Table 2. Material properties and characteristics of the implemented fibre reinforced polymer

Characteristic	Symbol	Value	Unit	Reference/Note
FRF Thickness	$t_{f,1}$	0.340	mm	(Sika, 2017)
Modulus of Elasticity	E_f	23,4500	N/mm^2	(Sika, 2017)
Characteristic Strength	f_{fk}	3,793	N/mm^2	(Sika, 2017)
Mechanical property of FRP	k_q	1.25	-	(Sika, 2017)
Environmental conversion factor	η_a	0.85	-	(CNR, 2014)
Ultimate design strength of FRP	f_{fd}	3,448	N/mm^2	(Sika, 2017)
Elongation at break	-	1.5	%	(Sika, 2017)
FRF Width	b_f	160	mm	(Sika, 2017)
FRP strain limit	-	-0.0031	-	(CNR, 2014)

A comprehensive study has been conducted to find the optimal number of columns and beams which need to be retrofitted by FRP wrapping in order to improve the structural performance (Teuchert et al., 2017). Analysing the structural performance under different arrangements of FRP application, the case with the highest seismic capacity increase is presented in this study. Accordingly, the full height of all columns at the ground floor and first floor beams needed to be wrapped with FRP layers, with fibres being applied in different directions. The impact of FRP wrapping is simulated through increasing the confinement factor in the concrete nonlinear modelling, however, the FRP effect on joints was not modelled. Considering the properties of the selected FRP, Table 3 represents the number of FRP layers applied to each member of the structure.

Table 3. Estimated number of FRP layers for each structural member

Member	**Structural Response (direction of FRP fibres)**	**Required number of FRP layers**	
		2-Storey, 2-Class	**3-Storey, 15-Class**
Columns	Flexural capacity (90°) Confinement (0°) Shear capacity (0°)	4 layers	3 layers
Beams	Shear capacity (90°)	1 layer	1 layer

A comparison of pushover curves obtained for both buildings before and after retrofitting are illustrated in Figure 5, in terms of base shear coefficient (base shear/mass) and roof drift ratio (top drift/total height). Due to the light weight of the FRP sheets, the retrofitting procedure does not lead to a considerable increase in the mass of the structure. Furthermore, FRP does not have a notable impact on the initial stiffness and therefore the fundamental period of the retrofitted structure stays the same as the original structure. Comparing the nonlinear static pushover outcomes indicates the improvement FRP has provided to the performance of the structures in terms of ductility and capacity. In particular, the results indicate an increase of about 10% and 6.2% in terms of strength for the 2-storey and 3-storey buildings respectively. In terms of ductility, if the ratio of drift at the ultimate strength (δ_{ult}) to that of yield strength (δ_{yld}) is considered, a rise of more than 100% in case of the 2-storey and an increase of 59% for the 3-storey building is observed. Therefore, an improvement of seismic performance can be expected in cases which FRP wrapping is implemented.

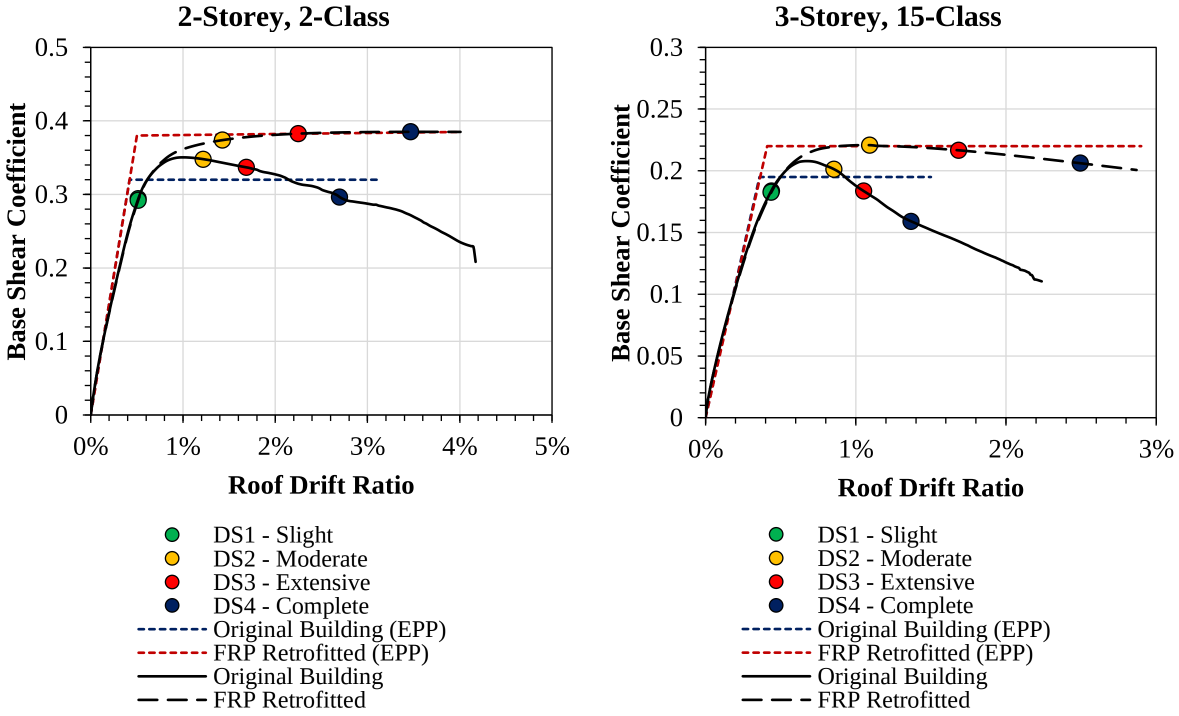

Figure 5. Static pushover and idealised curve of the analysed structures before and after retrofitting. Damage thresholds allocated to each building are also indicated.

6. FRAGILITY DERIVATION

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. To derive fragility function, the FRACAS (Fragility through Capacity Spectrum Assessment; Rossetto et al., 2016) methodology is chosen here. The methodology follows the capacity spectrum method, while utilising real (i.e., recorded during past events) earthquake ground motions. FRACAS idealizes and discretizes the structural capacity curve into a pre-defined number of analysis points. Each analysis point represents an inelastic single degree of freedom (SDoF) system, defined by the elastic stiffness, ductility and post-elastic properties according to the idealised capacity curve. The response of the SDoF under the applied earthquake record is assessed through the Newmark-beta time-integration method. The elastic and inelastic spectra of each applied ground motions is derived based on the response of the SDoF system. The performance point is evaluated at the intersection of the idealised capacity curve and the estimated response curve. The number of considered analysis points play a critical role in estimating both elastic and inelastic response and consequently the spectral acceleration (S_a) and spectral displacement (S_d) values of the performance point.

The capacity curves obtained for each structure, before and after retrofitting, have been idealised using a bilinear elastic perfectly plastic (EPP) curve, as illustrated in Figure 5. The ground motion intensity is characterized by the spectral pseudo-acceleration corresponding to the first-mode elastic vibration period and 5% damping ratio ($S_a(T_1)$).

6.1. Ground Motion Selection

Natural earthquake records can be implemented as an input in FRACAS to generate unsmoothed spectra as opposed to the conventional capacity spectrum method, which utilizes standardized design spectra. Therefore, the resulting performance points account for the natural variability of the seismic demand. For this study, the far-field ground motion set suggested in FEMA P-695 (2009) has been applied. The set of records are designed to be neither structure- nor site-specific and consists of 22 record pairs, each with two horizontal components for a total of 44 ground motions. The records have a moment magnitude (M_W) range of 6.5 to 7.6 with an average magnitude of 7.0 and all were recorded at sites located at a distance greater than or equal to 10 km from the fault rupture. According to the soil classification of NEHRP (FEMA-450, 2004), 16 sites are classified as stiff soil site (type D) and the remaining are classified as very dense soil (type C). The mean spectrum of the ground motions has an acceptable agreement with the code based design response spectrum of Philippines (NSCP, 2010), as demonstrated in Figure 6. The soil profile of Cagayan de Oro can be categorized as very dense soil and soft rock ($360 < V_{s,30} \leq 760$) and according to seismic zonation of the code, CdeO is located in zone IV with faults that are capable of producing large magnitude events ($M_w \geq 7.0$) and have a high rate of seismic activity indicating a peak ground acceleration of 0.4g. To ensures the records can trigger a vast range of structural responses, from elastic to nonlinearity and collapse, a scaling factor of 0.25 to 2.25 has been introduced to each selected record.

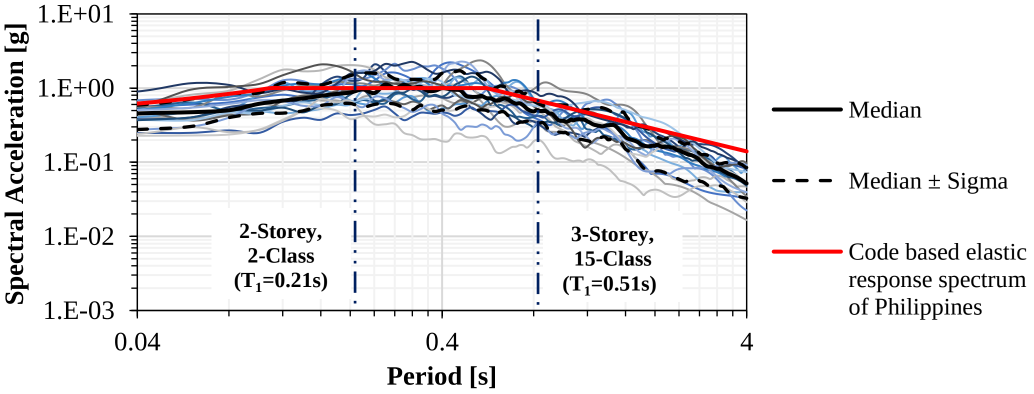

Figure 6. Response spectra of 22 records of P-695
and the code based elastic response spectrum (NSCP C101-10)

6.2. Damage Limit States

A critical stage in the fragility function derivation includes characterizing appropriate damage states and allocating rational global and local damage states. For the structure under study, maximum inter-storey drift ratio (MIDR) is employed as the engineering demand parameter (EDP), a quantifiable global indicator for each damage state. MIDR is a suitable choice for moment-resisting frames (MRF), since it relates the global response of the structure to joint rotations, in which most of the inelastic behaviour of a MRF is concentrated. In order to define appropriate damage states, the recommendations of a number of guidelines and codes such as HAZUS-MH MR4 (2003), HRC (Rossetto & Elnasai, 2003) and VISION 2000 have been reviewed. The suggested damage threshold for RC moment resisting frames are presented in Table 4.

Table 4. Damage thresholds suggested by different references
(C1L: Low-Rise, Concrete Moment Frame; C1M: Mid-Rise, Concrete Moment Frame)

Damage limit state	**HRC**	**HAZUS-MH**				**Vision 2000**
	Non-Ductile MRF	**C1L - Moderate Code**	**C1L – Low Code**	**C1M - Moderate Code**	**C1M- Low Code**	**RC buildings**
Slight	0.32%	0.50%	0.50%	0.50%	0.33%	0.50%
Moderate	1.02%	0.87%	0.80%	0.87%	0.53%	1.50%
Extensive	2.41%	2.33%	2.00%	2.33%	1.33%	2.50%
Complete	5.68%	6.00%	5.00%	6.00%	3.33%	> 2.50%

The selected damage thresholds in terms of MIDR employed for the fragility curves derivation are presented in Table 5, along with a brief description of the corresponding damage state. Similar to the thresholds suggested by HAZUS for low- and mid-rise moderate code reinforced concrete MRF, which are identical, in this study the same damage threshold values are utilised for both considered buildings. As the impact of FRP on the initial stiffness and period of the structure is negligible, the initial damage state (slight) will be identical for both cases. The most distinction in thresholds is observed in case of complete damage state, for which, the FRP retrofitting has considerably improved the ductility of both structures and hence the structure can withstand higher deformation prior to failure. Similarly, for moderate and extensive damage states, the threshold is increased as the structure's capacity and ductility has improved after the retrofitting is implemented. Figure 6, illustrates the damage thresholds on the pushover curves obtained for each of the buildings before and after retrofitting.

Table 5. Description of damage limit states and the assigned damage thresholds

Damage Limit State	**Performance Level**	**Description**	**Damage Threshold (MIDR)**		
			2-Storey, 2-Class	**3-Storey, 15-Class**	**FRP Retrofitted**
DS1 - Slight	Operational	Elastic behaviour of components. Limited yielding to a few members. No crushing of concrete (confined or unconfined).	0.59%	0.58%	0.59%
DS2 - Moderate	Life Safety	Concrete cover spalling at several locations for columns and beams (i.e. crushing of unconfined concrete).	1.88%	1.64%	2.20%
DS3 - Extensive	Near Collapse	Extensive crushing in some columns and/or beams at different floors, few concrete core crushing in columns. Max allowable FRP rupture strain = 0.016	2.77%	2.27%	3.80%
DS4 - Complete	Collapse	More than 40% of crushing in some columns and/or beams. Shear failure or total failure/cracking of columns and beams.	4.20%	3.24%	6.20%

The outcome of FRACAS analysis is presented in terms of IM versus EDP for both structures before and after retrofitting (Figure 7). The number and scaling of earthquake records, imply that 240 nonlinear dynamic runs were carried out for each model in FRACAS. The results indicate an improvement in performance of the structure after the FRP wrappings are implemented. Therefore, due to the enhancement in ductility and capacity, for a certain value of acceleration applied, the retrofitted structure is able to undergo a larger deformation. As expected the elastic performance of the structure at both phases are identical, similar to the results observed in the nonlinear static pushover.

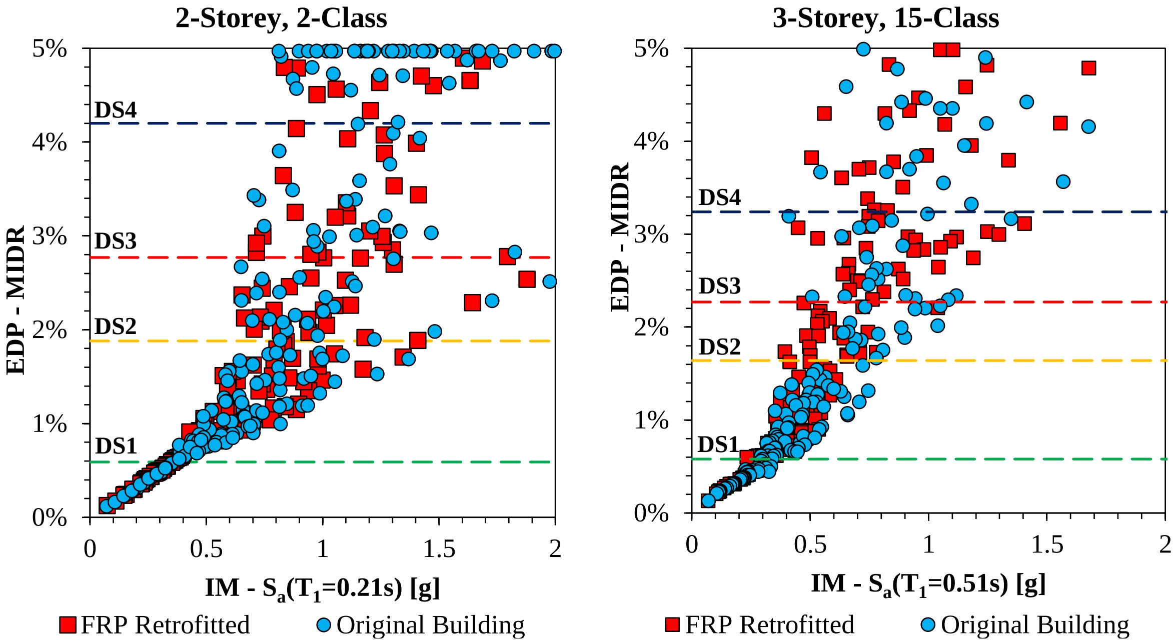

Figure 7. IM-EDP results obtained from FRACAS along with the damage thresholds implemented for the original building

6.3. Fragility Function Derivation

In order to derive the fragility functions for the IM-EDPs generated by the simplified method, a generalized linear regression method (GLM) with clog-log link function (Basöz & Kiremidjian, 1998) is applied to the performance points obtained through FRACAS. A thorough discussion of different regression procedures commonly used for developing fragility functions can be found in Lallemant et al. (2015) and Baker (2015). The fragility curves obtained for both structures before and after retrofitting are compared in Figure 8 and 9. The median and dispersion values for each fragility function are given in Table 6. As expected, the fragility curves representing the retrofitted structure have higher median for all damage states except the slight. The reason is the fact that FRP does not impact the structure’s stiffness and capacity up to this threshold, hence the structure behaves as its original state. The improvement observed in the performance of the structure after implementing FRP retrofitting, indicates lower vulnerability and damage ratio, which can consequentially result in a reduction of social and economic losses.

Table 6. Median (μ [g]) and Dispersion (β) values of fragility functions obtained for selected index buildings

	2-Storey, 2-Class				3-Storey, 15-Class			
Damage Limit State	**Original Building**		**FRP Retrofitted**		**Original Building**		**FRP Retrofitted**	
	μ	β	μ	β	μ	β	μ	β
DS1 - Slight	0.36	0.185	0.34	0.185	0.29	0.139	0.29	0.139
DS2 - Moderate	0.73	0.248	0.90	0.242	0.53	0.219	0.63	0.180
DS3 - Extensive	1.02	0.344	1.20	0.362	0.73	0.268	0.93	0.314
DS4 - Complete	1.43	0.440	1.66	0.417	1.04	0.320	1.28	0.352

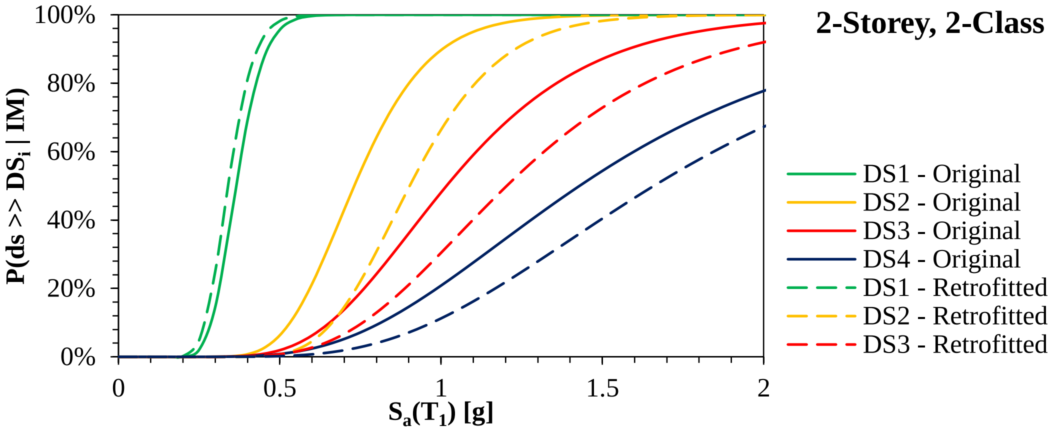

Figure 8. Comparison of fragility curves obtained for 2 Storey – 2 Class before and after FRP retrofitting

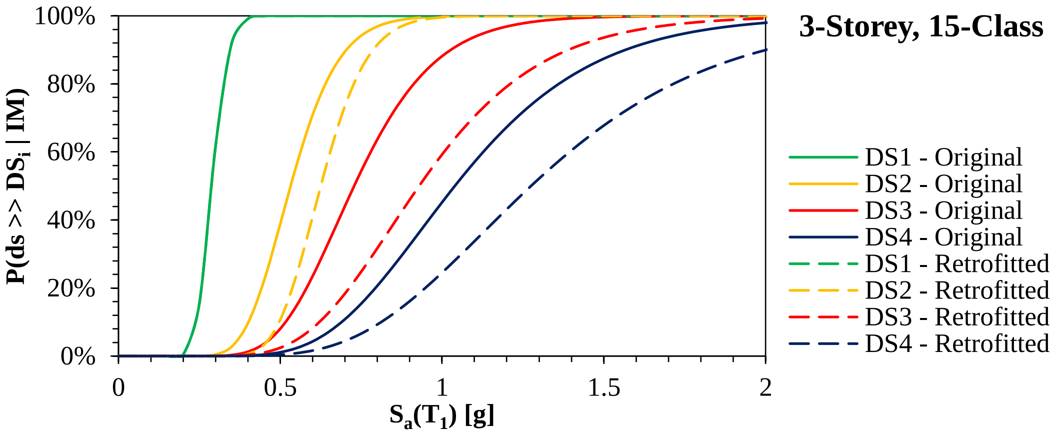

Figure 9. Comparison of fragility curves obtained for 3 Storey – 15 Class before and after FRP retrofitting

7. CONCLUSION

The Philippines is among the top global disaster hotspots, while being exposed to a wide range of natural and man-made hazards. Among these disasters, the country’s educational facility has suffered significantly, particularly under earthquake ground shaking. To analyse the performance of Philippine’s school infrastructure under probable earthquake intensities, two RC structures were selected as index buildings following the outcome of a regional visual survey and detailed drawings of the existing school buildings.

The performance of the structures was evaluated using nonlinear static analysis. The analysis results indicated a possibility of soft storey at the ground floor of both buildings. Therefore, FRP wrapping was employed as a retrofitting measure, applied to the entire height of all columns at the ground floor and first floor beams. The required thickness of FRP to provide sufficient shear and flexural capacity, as well as confinement were estimated using the latest provisions of CNR-DT 200.1R-13 (CNR, 2014). Comparing the structural behaviour before and after retrofitting indicated a considerable improvement in ductility and capacity of the structure, while no alteration was observed in total mass and initial stiffness of both buildings.

Moreover, to investigate the influence of FRP on the vulnerability of the structures, a simplified analytical method, FRACAS has been implemented using a suite of 22 scaled earthquake records. As expected the fragility curves indicated lower damage for any given intensity, except the initial damage state for which the structure behaves as its original state. The observed improvement in performance leads to lower vulnerability and damage ratio for the retrofitted buildings, which in return will reduce the social and economic losses of the school infrastructure. This is a preliminary study toward a more comprehensive framework on retrofitting of vulnerable school infrastructure in the Philippines, while considering various retrofitting options in accordance to full cost-benefit and loss analysis.

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