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SUITABLE SEISMIC RETROFITTING SOLUTIONS FOR TYPICAL MASONRY INFILLED REINFORCED CONCRETE SCHOOL BUILDINGS IN SRI LANKA

Mathavanayakam SATHURSHAN[1], Julian THAMBOO[2], Priyan DIAS[1], Tiziana ROSSETTO[3], Chinthaka MALLIKARACHCHI[1], Kushan WIJESUNDARA[4], Jonas CELS[3], Harikesan BASKARAN[3], Marco BAIGUERA[5] & Marta DEL ZOPPO[6]

Abstract: *School buildings in Sri Lanka are primarily designed and constructed to withstand only gravity load combinations. Most of the school buildings in Sri Lanka can be characterised as lightly reinforced concrete frame (RC) buildings, with infilled masonry walls (IMWs). In order to understand their seismic vulnerability and to find feasible retrofit solutions, this study numerically analyses the seismic performance of existing and retrofitted RC-IMW school buildings. The multi-criteria decision making (MCDM) method was then used to identify the most suitable retrofitting solution. Retrofitting options of adding IMWs (to the open ground storey), RC jacketing of columns (section enlargement), and a combination of both of these options are explored. Since the RC school buildings are lightly reinforced and provided with IMWs, a simplified approach was followed to account for the shear failure of RC columns due to seismic action. Three damage thresholds are established (damage limitation, significant damage and near collapse) to define the damage evolution under seismic loading. The numerical approach used is proven effective in understanding the seismic performances of the existing and retrofitted school buildings. The MCDM analyses reveal that the RC jacketing of columns only at the ground floor, is the most suitable retrofitting option, both in terms of seismic performance and economic feasibility.*

Introduction

The performance of school buildings to natural hazard events, such as earthquakes and tsunamis, require special attention due to their unique occupancy characteristics and significant post-disaster roles. Post-earthquake field assessments conducted globally reveal that the school buildings are prone to damage, even during low intensity events, as many of them are not designed according to modern seismic design codes. Moreover, the socio-economic costs associated with earthquake-related damages to school buildings are relatively high compared to other building classes. Therefore, the seismic vulnerabilities of existing school buildings should be thoroughly understood in order to improve their resilience.

The school buildings in Sri Lanka can be categorised as reinforced concrete (RC) frames, with infilled masonry walls (IMW) used as facades and partitions. Hitherto, school buildings in Sri Lanka have been designed only for gravity load combinations, with no seismic loading considered in the design stage. However, seismic records in the country reveal that there have been low to moderate intensity earthquakes in the past (Seneviratne et al., 2020). Especially, North, North-Western and Western regions are prone to highest seismic hazard within the country, where PGA values of these regions vary between 0.1 g to 0.25 g at bedrock level for the return period of 475 years. Therefore, it is imperative that relevant seismic hazards should be considered in designing critical national infrastructures, such as school buildings. Limited knowledge is available on the seismic response of existing school buildings in Sri Lanka, despite the performances of school buildings against natural hazards being extensively studied around the world (Del Zoppo et al., 2021; Clemett et al., 2022). Therefore, this study aims to assess the seismic performance of

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[1] Department of Civil Engineering, University of Moratuwa, Sri Lanka
[2] Department of Civil Engineering, South Eastern University of Sri Lanka, Sri Lanka
[3] EPICentre, University College London, London, UK
[4] Department of Civil Engineering, University of Peradeniya, Sri Lanka
[5] Department of Civil, Maritime and Environmental Engineering, University of Southampton, UK
[6] Department of Structures for Engineering and Architecture, University of Naples Federico II, Italy

existing school buildings in Sri Lanka, and to propose possible retrofitting solutions to reduce the risks.

The school buildings in Sri Lanka are constructed with certain RC frame and IMW typologies, as approved by the Ministry of Education (Cels et al., 2023). More details on the RC-IMW school building typology followed, are given in Section 2. A previous study on the seismic performance of these school buildings revealed that they are vulnerable to seismic loading, especially due to the irregular distribution of IMW arrangements, existence of an open ground storey (OGS) and inadequate flexural/shear capacities of the columns (Sathurshan et al., 2023). It was recommended that their vulnerability attributes should be mitigated to improve the seismic performance of these buildings. In the past, several solutions have been adopted to retrofit RC-IMW buildings, some of them being the addition of RC shear walls, jacketing techniques (using RC, FRP and steel plates), using viscous dampers, and base isolation. Although, different techniques are available to retrofit RC-IMW buildings, their applicability should be based on the seismic hazards, type of structures, target performance levels (e.g. stiffness and ductility) and adoptability. Therefore, it is important to select an optimal retrofitting solution based on the above mentioned factors.

Few studies have focused on the retrofitting solutions for school buildings considering their specific occupancy characteristics (Negro & Mola, 2017; W. Zhang & Nicholson, 2016). Seo, Kim and Kwon, (2018) determined the minimal number of RC columns to be retrofitted in an existing RC school building through an optimisation technique. Carofilis et al. (2020) investigated the retrofitting options for an Italian RC-IMW school building by considering expected annual lost and mean frequency of collapsed. Their analysis revealed that the FRP jacketing of columns and steel bracing within the ground floor bays improved the seismic performance of the particular RC-IMW school building. Moreover, Fernández et al. (2023) generated a data-driven methodological approach for RC and masonry school buildings by prioritising their risk level and including systematic retrofitting options through a machine learning clustering algorithm. Most of the retrofitting solutions contemplated in the past studies for RC-IMW school buildings so far are for high seismic hazard regions. The extent of seismic retrofitting solutions needed for buildings in low to moderate seismic regions are not well examined; and hence require thorough assessment. Though the seismic demand maybe low in these regions, minimal interventions would be required to reduce the seismic risk as the school buildings in these regions are normally not designed for any seismic hazard. This paper presents the details of different options considered to retrofit existing typical RC-IMW school buildings in Sri Lanka, which are not designed according to any seismic provisions. Also, the retrofitting solutions contemplated in this study are based on the low to medium seismicity as well as the adoptability in terms of economic and social contexts in Sri Lanka. Subsequently, a multi-criteria decision making (MCDM) method was adopted to select the most suitable retrofitting option based on the seismic performance and economic criteria.

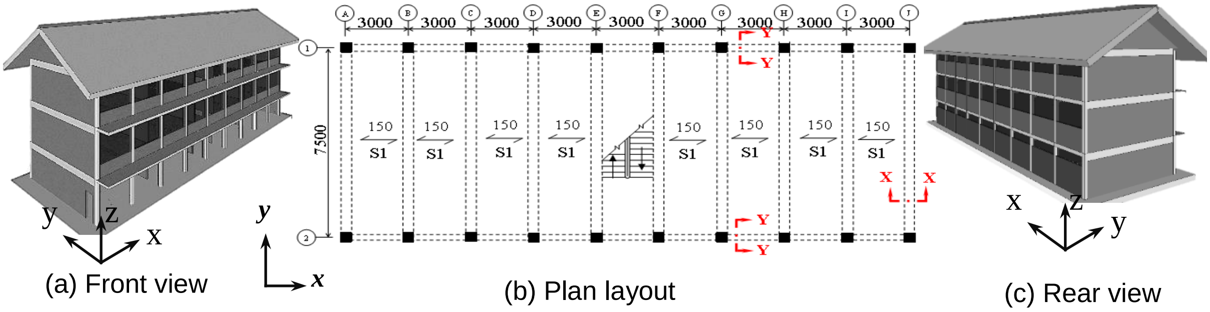
Typical RC-IMW school buildings

The layout of a typical RC-IMW school building in Sri Lanka, comprising two rows of columns (front and rear sides), is shown in Figure 1. Typical reinforcement detailing used for these buildings can be found in Sathurshan *et al.* (2023). Although, the frame type is consistent across RC school buildings in Sri Lanka, significant variations prevail in terms of IMW arrangements and configurations. Some of the school buildings surveyed are shown in Figure 2, where the different IMW configurations and arrangements identified, are highlighted. No definite relevance was found between the building typologies and IMW arrangements and configurations. Furthermore, it was also noted that the thickness of IMWs varies in the range of 110 mm to 220 mm, implying that single (SW) or double brick/block (DW) bonded IMWs were used within the frames. Also, these types of school buildings are constructed with an open ground storey (OGS) at the front, and partially filled IMWs at the rear, as shown in Figure 1. This makes the buildings irregular in vertical and plan directions, and may lead to the formation of soft-storey mechanism under the lateral seismic action. Subsequently, these vulnerability attributes should be accounted in the seismic performance assessment of these school building typologies.

Retrofitting solutions

In order to mitigate the seismic risk of these RC-IMW school building types, five retrofitting options were considered. Primary objective of retrofitting these school buildings is to improve the seismic performances and to undergo minimal non-structural repairable damages during an expected seismic action, hence it will enable to occupy the school buildings after an earthquake in Sri

Lankan context (with minor non-structural repairs). The retrofitting options considered are (1) adding IMWs to OGS RC frames and altering IMWs to upper floors to make a uniform distribution of IMWs with central windows (O1); (2) the RC jacketing of ground storey columns to the OGS (O2); (3) combination of the first and second solutions (O3); (4) the RC jacketing of columns along the entire building height with partially filled IMWs (O4); and (5) a combination of first and fourth solutions (O5). These retrofitting solutions are schematically illustrated in Figure 3. The rationale of adding IMW to the OGS frames was to alleviate the soft-storey mechanism forming at the ground floor and also to minimise the vertical and plan irregularities in the building. The RC jacketing of columns is a well-established method for improving the lateral stiffness, resistance and ductility of buildings. Previous seismic analyses of these RC-IMW school buildings revealed that their failure under seismic loading was primarily triggered by the flexural/shear failure of columns at the ground storey level. Therefore, in jacketing the columns, the two sub-solutions of jacketing only the ground floor columns (O2) and the jacketing of the columns to the entire height of the building (O4) were considered. Also, the combinations of adding IMWs with RC jacketing (O3) and (O5) were also examined to verify their efficacy.



(a) Front view (b) Plan layout (c) Rear view

Figure 1: RC frame typologies used in Sri Lankan school buildings (dimensions are in mm).

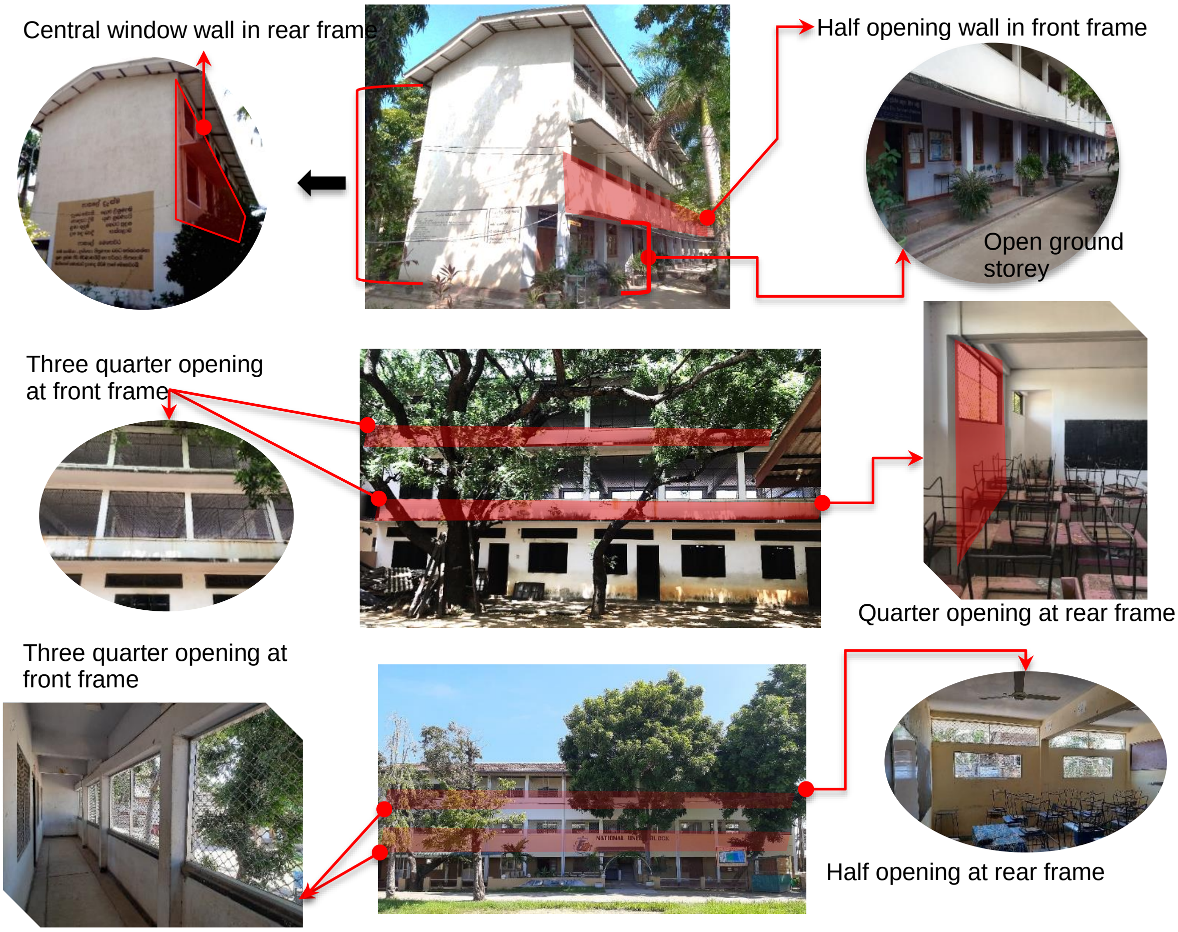
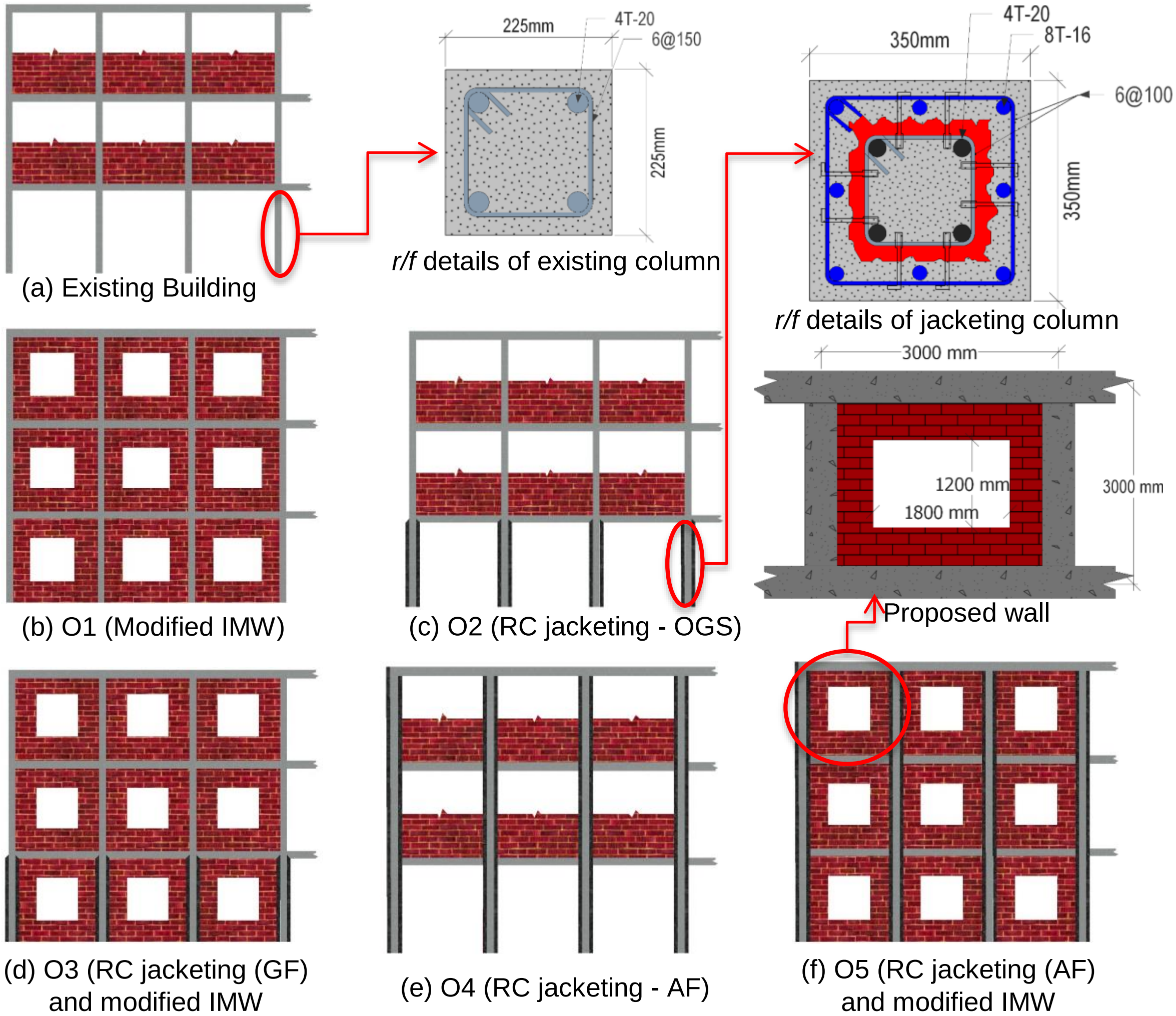


Figure 2: RC-IMW school buildings with irregularities.



(a) Existing Building

r/f details of existing column

r/f details of jacketing column

Proposed wall

(b) O1 (Modified IMW)

(c) O2 (RC jacketing - OGS)

(d) O3 (RC jacketing (GF) and modified IMW

(e) O4 (RC jacketing - AF)

(f) O5 (RC jacketing (AF) and modified IMW

Figure 3: Retrofitting options considered (dimensions are in mm).

Seismic analyses of existing and retrofitted buildings

The seismic analyses of the school building were implemented through the OpenSees (OS) programme (OpenSees, 2021). The method followed to establish OS models of these school buildings and their seismic performance has already been developed by the authors, and details are given in Sathurshan *et al.* (2023). The procedure developed to evaluate the seismic performance of the school buildings through nonlinear pushover analyses is presented in Figure 4. The RC elements were modelled using force-based nonlinear beam-column elements; and joints were represented using concurrent nodes. The slab elements were modelled as rigid diaphragms. The constitutive behaviour of concrete and steel were represented by *Concrete04* and *Steel01* models available in OS material library, respectively. The IMWs were represented as single equivalent diagonal struts, according to the method given in FEMA-356 (2000).

These typical school buildings can be characterised as lightly RC-IMW buildings. Therefore, the torsional effects and shear demand (in the columns) arising due to the irregularities in IMW arrangements and configurations were integrated in the numerical procedure developed. A simplified post-processing procedure was used to account for the shear failure of RC columns. For that purpose, the Response-2000 (Bentz, 2001) sectional analysis software was used. The Response-2000 uses modified compression field theory (MCFT) to compute the axial-shear-flexural interaction capacities of RC sections. In order to incorporate the shear behaviour of the member, the shear demand obtained from the OS out-put data was compared with Response-2000 (iteratively), and when the shear demand exceeds the shear capacity, the member was assumed attained the shear capacity. The material properties (concrete, steel, and masonry) used in the building models and further details on the seismic analysis procedure can be found in Sathurshan *et al.* (2023). Three distinct damage stages were identified according to the damage progression of the building analysed, they are (1) cracking of IMW (assumed to occur when the strut force reaches 70% of the IMW strength), (2) crushing of IMW, (3) plastic hinge formation in the columns (more than 50% of the GF columns) or shear failure of the columns (more than 50% of the GF columns), whichever occurs first. For the buildings analysed, these three damage states correspond to the limit states of (1) Damage Limitation/DL (2) Significant Damage/SD and (3) Near Collapse/NC for the EN:1998-3 (2005) provisions.

As part of the analyses, a three storey RC-IMW school building (as shown in Figure 1) was assessed using the same procedure. The performance of the IMW altered retrofitted building (O1) was analysed by adding equivalent diagonal IMW struts to the OGS bays at the ground floor level. The RC column jacketing configuration was determined using the ACI 562 (2019) and the reinforcement detail provided is shown in Figure 3. The jacketed column sections were assigned to the building model as a retrofitting solution, and then analysed. Finally, the combined retrofitting options (altering IMW walls and RC jacketing) were analysed by including both modifications in the OS models (adding equivalent diagonal struts and enlarged column sections).

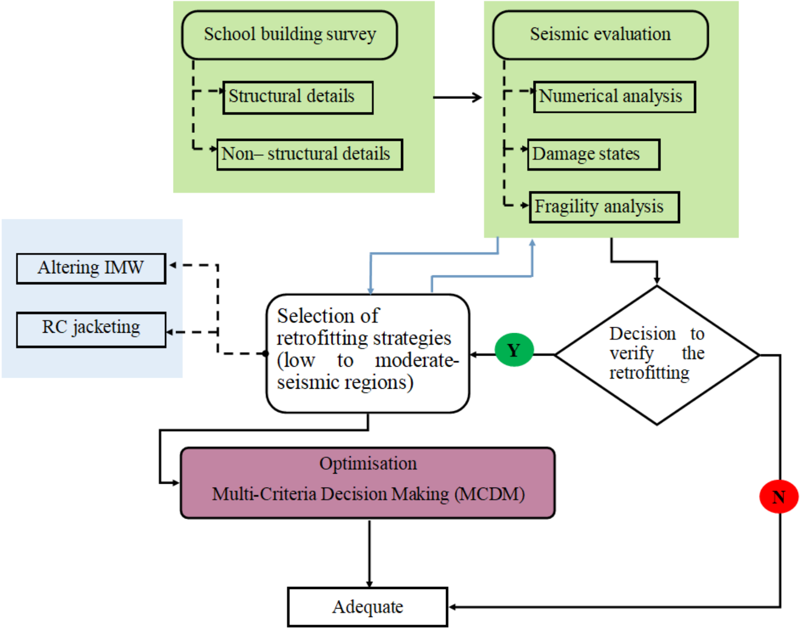


Figure 4. Methodology of the study

Pushover curves of existing and retrofitted buildings

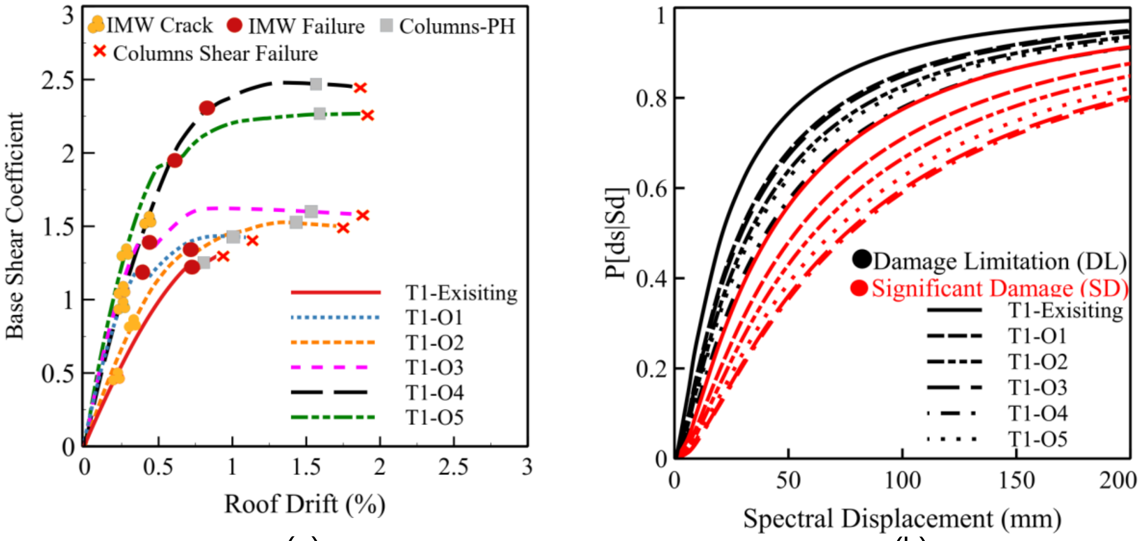
The pushover curves obtained for the existing and retrofitted, three storey RC-IMW school buildings are presented in Figure 5(a). In order to make the comparisons consistent, base shear coefficients are plotted against the roof drift levels obtained. For brevity, only the pushover curves obtained in x direction (longitudinal) is presented in Figure 5(a). The failure sequence – i.e. IMW failure, plastic hinge (PH) formation and shear failure of the columns - of the buildings are marked on the pushover curves. In order to effectively compare the seismic performances of the buildings analysed, engineering parameters such as, the first natural period (T), the base shear (V_s), the initial stiffness (K_{in}), and the roof drift ratio (DR) corresponding to different damage stages are given in Table 1. It can be noted that all the retrofitting options have improved the seismic performance in terms of base shear and drift capacities attained. Obviously, the stiffness of the buildings increases with the retrofitting options considered. When only IMWs are altered (O1), the stiffness of the building increases about 117%. RC jacketing at ground floor (O2) increases the stiffness only about 13%, but jacketing for full storey height (O4) increases it about 131%.

In terms of drift values obtained, in general, O3 offers better performance compared to other retrofitting options considered. The increase in drift levels in O3 retrofitted building compared to existing building are 21%, 51% and 101% for damage states DL, SD, and NC, respectively. The reduction in drift levels in O4 and O5 compared to O3 could be due to the increase in stiffness coupled with reduction in period of the buildings.

The seismic fragility curves for building were derived based on the natural logarithm function and normalised standard deviation of damage states considered. Only the fragility curves for DL and SD damage states are presented in Fig 5(b) for existing and retrofitted buildings, as these damage states have been explicitly used in the MCDM method to select the most suitable retrofitting option in terms of different criteria used, those details are given in the next section.

Cases	T (s)	V_s (kN)	K_{in} (kN/mm)	DR_{DL} (%)	DR_{SD} (%)	DR_{NC} (%)
T1-Existing	0.76	1130	18.6	0.29	0.61	0.80
T1-O1	0.67	1632	40.3	0.33	0.50	0.97
T1-O2	0.63	1367	21.1	0.40	0.74	1.24
T1-O3	0.54	1889	53.8	0.35	0.92	1.63
T1-O4	0.53	2315	42.9	0.42	0.89	1.52
T1-O5	0.52	2729	63.2	0.48	0.87	1.67

Table 1. Parameters determined from the pushover curves of the existing and retrofitted buildings analysed.



(a) (b)

Figure 5. (a) Pushover curves of existing and retrofitted school buildings and (b) the seismic fragility curves for DL and SD.

Multi-Criteria decision making process

The seismic performances of the retrofitted school buildings revealed that all the options have improved the performances in terms of lateral load and displacement capacities. However, implementation of retrofitting schemes are not only dependent on the structural benefits, but should also be based on economic factors such as initial cost, maintenance cost, and disruption of use. Therefore, a best retrofitting solution has to be selected among the factors mentioned above. For that purpose, the MCDM method was used in this study. The MCDM method enables the appraisal and comparison of a set of options, when a decision has to be made from multiple criteria. This method was introduced in management decision making, but later used by Caterino *et al.* (2008) to find the best seismic retrofitting method for a prototype RC building. A few other studies also used this method to suggest the most suitable retrofitting option for their building configurations (Clemett et al., 2022; Gentile & Galasso, 2021), however they are mostly used for the buildings in high seismic regions. Nonetheless, the MCDM method was used to compare the suitable retrofitting methods for the RC-IMW school building considered, in the context of low to moderate seismicity and well as economic criteria relevant to Sri Lanka. The criteria considered for the purpose are given in Table 2. Out of six criteria considered, three of them involve engineering parameters (lateral capacity; and attainment of damage limitation and significant damage states); while the other three are based on economic considerations such as initial cost, maintenance cost, and retrofitting duration. The relative importance for each criterion was assigned using the Analytic Hierarchy Process (AHP) and pairwise comparisons were made by the authors, and they are indicated against each criterion in Table 2. All the criteria considered are objective in nature, therefore values were directly computed. However, the consistency and sensitivity of the criteria were analysed based on the weights assigned. The first eigenvalue of the decision matrix obtained was used to determine the weight of each criterion. The consistency of the pairwise comparison among criteria considered was checked as suggested by Saaty (1987), and a consistency ratio of 2.13% was obtained, which is less than 10%, and thus acceptable.

Criterion	Initial cost (C1)	Maintenance cost (C2)	Retrofitting duration (C3)	Lateral capacity (C4)	Damage limitation (C5)	Significant damage (C6)	Weight
Initial cost (C1)	1.0	9.0	7.0	1.0	1.0	1.0	0.233
Maintenance cost (C2)	0.11	1.0	1.0	0.2	0.14	0.11	0.030
Retrofitting duration (C5)	0.14	1.0	1.0	0.2	0.14	0.11	0.031
Lateral capacity (O4)	1.0	5.0	5.0	1.0	1.0	0.33	0.164
Damage limitation (C5)	1.0	7.0	7.0	1.0	1.0	0.33	0.184
Significant damage (C6)	1.0	9.0	9.0	3.0	3.0	1.0	0.357

Table 2. Selected MCDM criteria and the determined weights ($\lambda_{max} = 6.132$, CR = 2.13%)

Subsequently, the assessment process of each criterion is given below:

Initial cost: The initial costs of the retrofitting methods were calculated based on the costs of the retrofitting processes involved, e.g. demolitions, material, labour, retrofitting and finishing. Also, a contingency of 10% was included in calculating the initial cost, which is a usual practice in estimating project cost for any project. Consequently, the initial costs calculated for O1, O2, O3, O4, and O5, are US$2749, US$4437, US$7186, US$13461 and US$16211, respectively.

Maintenance cost: Computing the maintenance cost is a difficult process, as there are no systematic maintenance benchmarks for school buildings in Sri Lanka. Therefore the methodology adopted in Caterino *et al.* (2008) and Gentile and Galasso (2021) were used. For all the retrofitting options considered, an inspection and possible repair of cracks/repainting every ten years were considered as the maintenance requirement. The service life of the building was assumed as 50 years. The maintenance costs for the options O1 (US$326), O2 (US$521), O3 (US$647), O4 (US$963) and O5 (US$1099) were thus obtained.

Retrofitting duration: Total time needed for a retrofitting was calculated based on the retrofitting processes involved from initial demolition works to final finishing works. A crew comprising an engineer, a site supervisor, two masons and four non-skilled labourers was considered for the retrofitting option O1. For the RC jacketing works (O2), a crew including an engineer, site supervisor, four skilled labourers and four non-skilled labourers were considered. A working day was assumed as eight hours, and accordingly, the total retrofitting durations were determined. The durations of the retrofitting for the selected options O1, O2, O3, O4 and O5 are 12, 25, 37, 76 and 88 days, respectively.

Base shear coefficient, damage limitation (DL) and significant damage (SD): The lateral capacities achieved through different retrofitting methods are based on the peak base shear coefficients obtained (Table 3, C4). Further, to assess the deformation capacities of the retrofitted buildings (against certain damage states), the pushover curves obtained were converted to capacity curves; i.e. to verify demand and capacity of the building against the seismic hazard in Sri Lankan condition (Seneviratne et al., 2020). For this purpose, the N2 method was used (Dolšek & Fajfar, 2008). To perform the N2 method, reduction ($R\mu$) and ductility (μ) factors were computed specific to the building cases analysed. Figure 6 illustrates the application of the N2 method using the capacity demand curves, where the bilinear idealization of the capacity curves were used. Table 3 (C5 and C6) gives the spectral displacement values obtained for retrofitted buildings corresponding to different damage states considered (DL and SD). The seismic hazard specified for North and North-western regions in Sri Lanka was considered in this study. The response spectrum used in this study was obtained from Seneviratne et al. (2020). It is noted that all retrofitted structures cross the elastic spectrum in the linear elastic range. The performance of existing structure is compared to the inelastic spectrum for its maximum ductility (1.15), and is seen to fail. Also, it can be noted from Table 3 and Figure 6 that all the retrofitting methods considered have achieved the required seismic demand for the buildings (if the demand curve exceeds the capacity curve, the building is considered to be in a state of damage). Note that the values for C4, C5 and C6 in Table 3 are given as inverse values, since higher values for them would be better; whereas direct values are used for C1, C2 and C3, since lower values are better (the MCDM is set up as a “minimization” exercise).

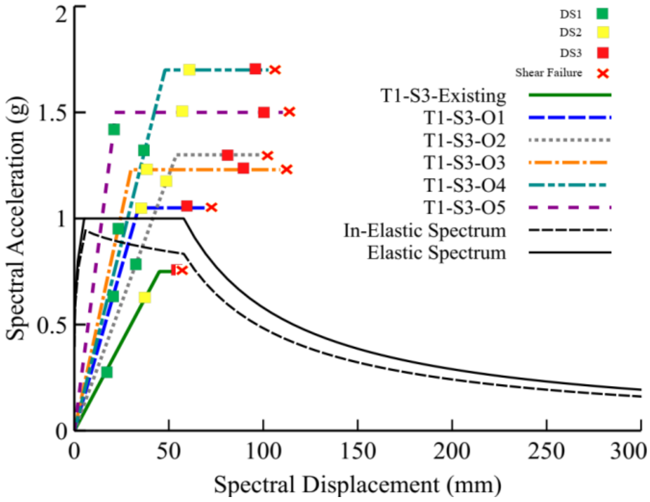


Figure 6. PGA capacity measurements according to N2 method.

In order to identify the most suitable retrofitting option from a group of five options (O1-O5) considered, the MCDM technique was applied in the final step of the procedure. Table 3 summarises the parameters assigned to each option, based on the selected criteria. The decision matrix (*D*) is represented based on the parameters, $D = [x_{ij}]$, obtained for each option, $i = \{1,2\ldots,5\}$, and criterion, $j = \{1,2\ldots,6\}$. It is important that all the values of x_{ij} are included in the decision matrix as they are required as the initial input for the TOPSIS method (Yoon & Hwang, 1981). Then the matrix *D* has to be normalized (linearly, and each criterion separately), in order to make consistent comparisons.

	C1 ($)	C2 ($)	C3 (days)	C4	C5	C6
O1	2749	326	12	0.699	0.0350	0.0189
O2	4437	521	25	0.654	0.0305	0.0168
O3	7186	647	37	0.617	0.0340	0.0133
O4	13461	963	76	0.405	0.0289	0.0144
O5	16211	1099	88	0.440	0.0249	0.0130

Table 3. Decision Matrix (D)

The MCDM method involves a geometrical concept that measures the shortest distance to an ideal solution (O*) and the longest distance to a negative ideal option (O-) to calculate the relative ranking of the available options. The normalized graphical representation of the decision matrix can be seen in Figure 7, with the x_{ij} matrix being normalized as $R = [r_{ij}]$. Consequently, the weights of the criteria in Table 2 were multiplied by the normalized matrix, *R*. Then, the ranking of the retrofitting options was determined.

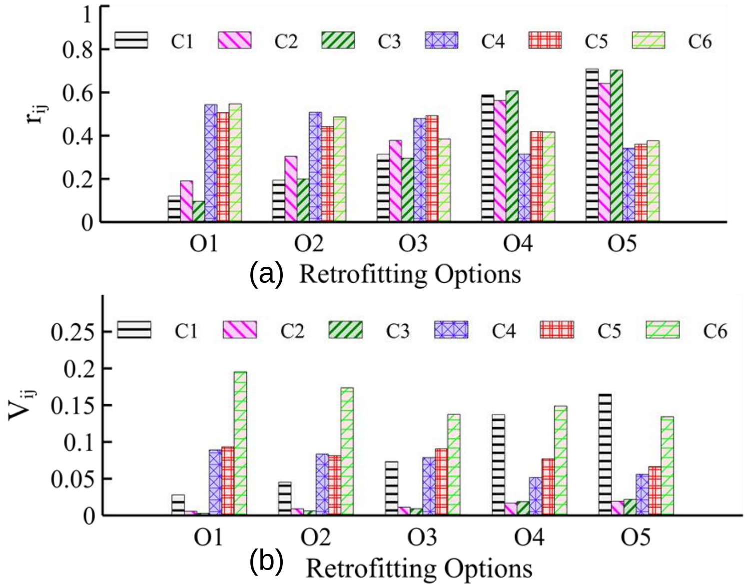


Figure 7. (a) Normalised performance (r_{ij}) and (b) weighted normalised performance (V_{ij}) with respect to comparison among options and criteria

The MCDM method employs a six-dimensional space to represent each option (O1-O5) and the fictitious alternatives (O* and O-), where the performance of each option along the C1-C6 criteria is mapped onto respective axes. Table 4 shows the relative closeness of each option adopted in the study, where Si and Si* are the distances of the options Oi (*i* = {1, 2...,5}) to O* and O-. It can be noted from the Ci* values obtained, that the option O2 (Ci* = 0.691) is seen to be the ideal solution mooted (shortest distance from the ideal solution and the near furthest distance from the worst solution). However, O1 and O3 options are also closer to the O2, where their Ci* values are 0.645 and 0.653, respectively.

Options	Si-	Si*	Ci*
O1	0.139	0.076	0.645
O2	0.124	0.056	0.691
O3	0.110	0.059	0.653
O4	0.068	0.112	0.377
O5	0.075	0.139	0.348

Table 4. Relative closeness to the ideal solution of retrofitting options

Conclusion

The most suitable seismic retrofitting option for a RC-IMW school building in Sri Lanka, which is in a low to moderate seismic region, was investigated. For that purpose, two different retrofitting options (adding/altering IMWs and RC jacketing of columns) were posited, with five different combinations among them. In order to be more realistic in determining the suitable retrofitting option, the MCDM method was used incorporating both engineering (lateral capacities and drift limits) and economic parameters in the Sri Lankan context. The numerical method employed to analyse the seismic performance of RC-IMW buildings involves a simplified, yet needed procedure to capture the shear failure of columns due to the presence of IMWs. Among the retrofitting options considered, the O2 option (i.e. adding IMW with RC of columns only at ground floor) has emerged as the most effective solution, in terms of seismic performances as well as other criteria considered. Further studies are needed to extend these analyses to other school building typologies existing in the country. Furthermore, sensitivity analyses will be carried out in the future to verify the reliability of the MCDM criteria used.

Acknowledgements

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