Seismic retrofitting of masonry infilled RC buildings in low- to moderate-seismic regions: Case study of typical Sri Lankan school buildings

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Abstract

Seismic retrofitting solutions for reinforced concrete (RC) school building types in high-seismic regions are extensively reported in the state-of-the-art. Conversely, limited studies have focused on the extent of retrofitting needed for RC school buildings in low- to moderate-seismic regions. To explore this aspect, seismic retrofitting options for RC school buildings in Sri Lanka are investigated. Three retrofitting options are examined: (1) adding/altering masonry infill walls (MI walls) to reduce irregularity in buildings, (2) RC jacketing of columns and (3) a combination of adding/altering MI walls and RC jacketing. These retrofit options are applied to a common typology of Sri Lankan MI-RC school buildings, considering two and three storey height variations. A simplified numerical modelling approach that accounts for the contribution of MIs, the shear failure of RC column and torsional effects is adopted to analyse the performance of the school buildings with and without retrofit. Based on the analyses, three damage states are defined: damage limitation (DL), significant damage (SD) and near collapse (NC). Finally, a multi-criteria decision making (MCDM) method is used to determine the optimal retrofitting option for the considered school building typology, considering engineering and economic parameters. The optimal retrofit solution for the three-storey MI-RC school building is found to be jacketing of ground floor columns. Conversely, for the two-storey MI-RC school building, alteration of infill walls (MI walls) is deemed optimal. Finally, a sensitivity analysis is carried out on the MCDM method.

Keywords: *Reinforced concrete buildings; Retrofitting; Seismic vulnerability; Masonry infills; RC jacketing; Shear failure; Multi-criteria decision making (MCDM)*

1 Introduction

Recent destructive earthquakes around the world have demonstrated the structural vulnerability of pre-code buildings, as well as in newer buildings that are not designed to modern seismic codes (Karatzetzou et al. 2023; Opabola et al. 2023). Even though all structures with seismic deficiencies should be assessed, a greater emphasis should be given to the assessment of disaster critical structures such as schools, hospitals and bridges to reduce recovery times (Asadi et al. 2019; Fu et al. 2021; Zizi et al. 2021, 2023; Poudel et al. 2023). Several studies have been conducted so far to understand the seismic performance of school buildings in different regions, and various retrofitting measures have been proposed to reduce their seismic fragility (O'Reilly et al. 2018; Gentile et al. 2019; Ruggieri et al. 2020; Masi et al. 2021). However, most studies conducted in the past have evaluated the seismic fragility of school buildings in high-seismic regions, subsequently proposing structural retrofitting schemes such as jacketing of structural elements, and adding reinforced concrete (RC) shear walls, steel bracings, seismic dampers and base-isolation (O'Reilly et al. 2018; Seo et al. 2018; Carofilis et al. 2020; Ruggieri et al. 2021). In contrast, the seismic performance of school buildings in low- to moderate-seismic regions are much less studied. Many schools built in these regions are not seismically designed, and can have poor seismic performance even for relatively small seismic events. This implies the need for a certain level of retrofitting; however, given the lower seismic hazard intensity, the level and type of seismic retrofitting options that are appropriate and economically viable for those buildings are not well explored.

This paper explores the seismic performance and possible retrofitting options for RC buildings in low- to moderate-seismic regions, by using typical RC school buildings in Sri Lanka as case studies. The majority of structures in Sri Lanka, including school buildings, are not designed for seismic actions, given the perceived lack of seismic activity. However, recent seismic hazard studies have revealed that the country should be considered as being a low- to moderate-seismic region (Gamage and Venkatesan 2019; Uduweriya et al. 2020), more details on the seismic hazard in Sri Lanka are provided in Section 4.4. There is hence a real concern regarding the seismic risk of school buildings in Sri Lanka.

Sri Lankan school buildings are typically constructed with RC frames, infilled with masonry walls (MI walls) for partitioning and facade purposes. Previous studies on the seismic performance of these school building typologies revealed that they are vulnerable to seismic loading, especially due to the irregular distribution of MI arrangements used, existence of open ground storey (OGS) and inadequate flexural/shear capacities of the columns (Sathurshan et al. 2023a, b). The influence of these attributes on the seismic performance of the buildings have been extensively studied around the world (Pavese et al. 2017; Choudhury and Kaushik 2018; Di Trapani and Malavisi 2019; Romano et al. 2021; Mucedero et al. 2021; Sathurshan et al. 2023a). However, the required extent of retrofitting solutions needed for MI-RC of buildings in low- to moderate-seismic regions are not well explored in the literature. As postulated above, costly seismic retrofitting schemes such as base-isolation and dampers may not be needed for buildings in low- to moderate-seismic regions, and would be prohibitively expensive in a Low- to Middle-Income Country (LMIC) like Sri Lanka. However, some minimal interventions are needed to strengthen these buildings against prevailing seismic hazard. Furthermore, the intervention solutions should be appropriate for the local construction practices and economically viable in order to be realistically implemented (Di Trapani et al. 2020; Requena-Garcia-Cruz et al. 2021).

A number of previous studies have adopted systematic approaches to choose optimum seismic strengthening solutions based on a number of criteria. Such approaches include index-based (Requena-García-Cruz et al. 2019), cost-benefit (Sousa and Monteiro 2018; Cardone et al. 2019), resilience based (Cimellaro 2013) and multi-criteria decision making (MCDM) (Caterino et al. 2008; Gentile and Galasso 2021). Gallo et al. (2022) have analysed the applicability of these approaches to select a retrofitting scheme for an Italian school building located in a high-seismic region. It was reported that different retrofitting types are found to be “optimum” when the different approaches are used; however, it was shown that MCDM is the most versatile method as it allows addition of multiple decision criteria to select the viable retrofitting scheme. Recently, MCDM has also been adopted for the selection of the optimum seismic and energy performance enhancing retrofit solution for an Italian school by Clemett et al. (2022, 2023). These studies suggest that the MCDM method is adaptable for use in different contexts; hence it is selected for use in this paper.

The approach followed herein for determining the optimum retrofitting solution for MI-RC school buildings in Sri Lanka is illustrated in Fig 1. The main retrofitting options considered in this study are (1) adding/altering MI wall arrangements, since irregular MI walling configurations and arrangements are provided in these school buildings - these details are explained in Section 2.1; (2) RC jacketing of columns and (3) combinations of the first and second options. These retrofitting options are considered as minimum possible interventions, since they are technically and economically feasible for use in Sri Lanka, while considering the low- to moderate-seismicity. In the following sections, details of the existing two- and three-storey MI-RC school building types analysed are presented, together with the retrofitting options considered. The seismic performances of existing and retrofitted MI-RC school buildings are then presented, and the MCDM steps followed to determine the optimum retrofitting solution for each school type explained. Finally, the key findings of this research study are summarised.

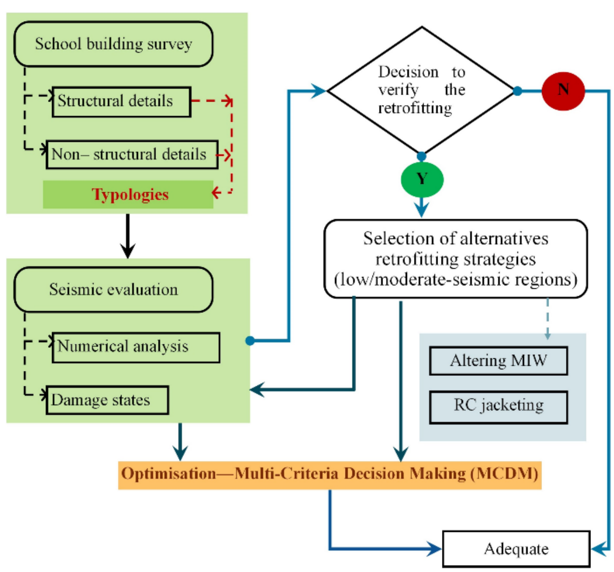


Fig 1. Methodology of the study.

2 Typical MI-RC school buildings

School buildings are generally constructed with a limited set of typologies in most countries. This is the case for Sri Lanka, where single-storey school buildings are typically constructed out of unreinforced load-bearing masonry, whereas multi-storey school buildings are built with MI-RC configurations (Nanayakkara et al. 2016; Del Zoppo et al. 2021; Cels et al. 2023a, b). In this study, retrofitting options are investigated only for typical Sri Lankan MI-RC school buildings. The structural and non-structural features of these buildings are explained in the following sub-sections.

2.1 Structural features of the school buildings

In Sri Lanka, MI-RC school buildings are typically constructed to be two or three storeys in height (S2 and S3), with storey heights of approximately 3 m. The layout of a typical school building is illustrated in Fig 2, together with the section details of typical RC elements (columns and beams). The same RC element section sizes and detailing are used in schools regardless of the number of storeys (Cels et al. 2023a). The buildings comprise two rows of columns (front and rear) connected by transverse beams (525 mm × 225 mm). The columns are designed to resist only gravity load combinations as per BS 8110-1 (1997), and have a size of 225 mm × 225 mm. It should be highlighted that such existing school buildings are not designed and detailed against possible seismic hazards.

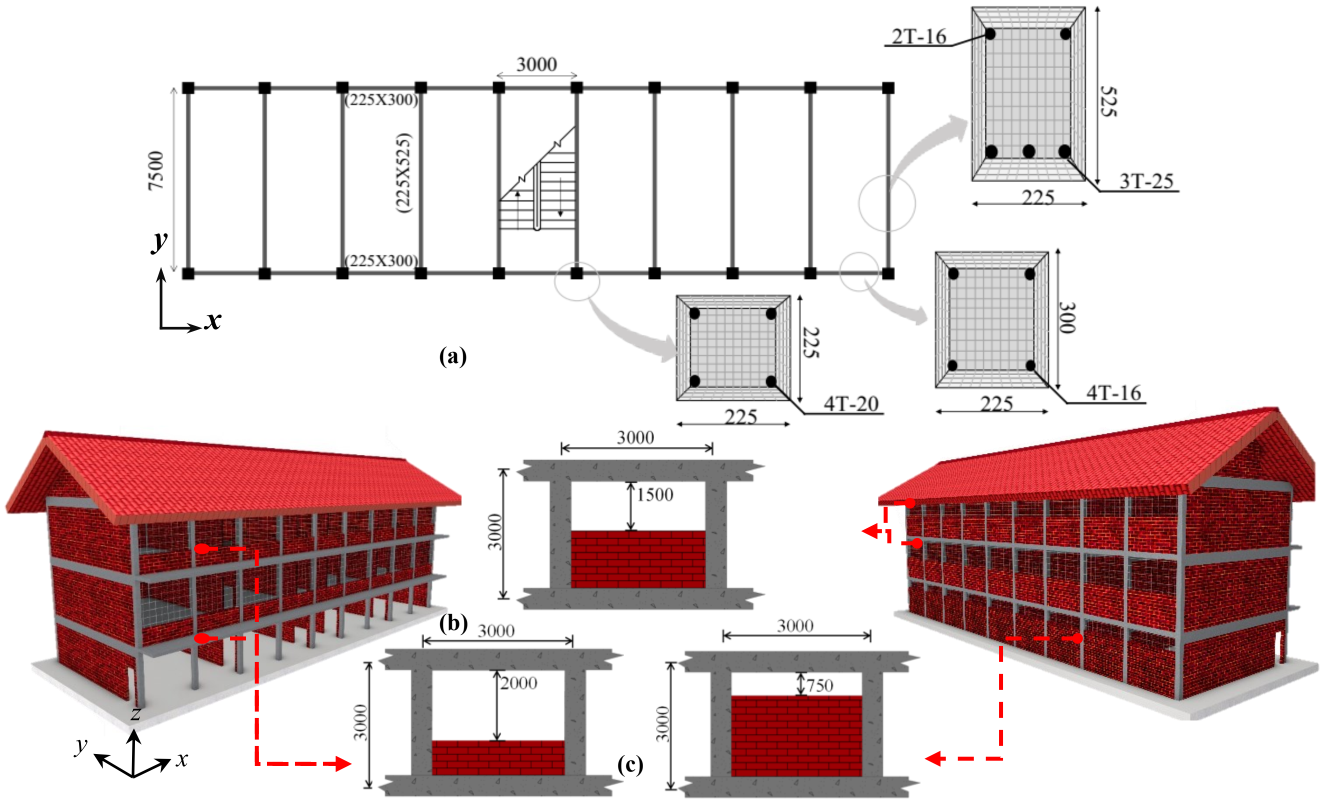


Fig 2. (a) layout of T1 building, (b) three storey T1 building and (c) MI configurations.

2.2 MI arrangements in school buildings

Although the structural frames of the two and three storey school buildings are fairly consistent, they vary significantly with respect to the MI arrangements and configurations used to partition and provide façades to the classrooms. These buildings are generally built with an Open Ground Storey (OGS) on the front side, and have irregular MIs on other sides (e.g. rear) and at different floor levels (along the *x* direction of the building as indicated in Fig 2). Fig 3 illustrates some existing school buildings with OGS and irregular MI arrangements. More details on the structural and non-structural features of these typical MI-RC school buildings can be found in Sathurshan et al. (2023a, b) and Cels et al. (2023a).

These irregularities in MIs have the tendency to create a soft storey mechanism in the buildings under seismic loads. This vulnerability attribute has been observed in many of the damaged/collapsed buildings in the past (Formisano et al. 2020; Gkournelos et al. 2021). Also, the existence of half opened (HO), three-quarter opened (TO), and quarter opened (QO) MIs, i.e.

partial MIs, have the tendency to induce short column effects, as the columns in these buildings are not designed to take large lateral actions. Additionally, irregular MI arrangements on the plan and in the vertical directions add to mass and stiffness irregularities, which in turn can result in high torsion under earthquake loads, increasing the vulnerability of such buildings. Any proposed seismic retrofitting solution must improve these existing vulnerability attributes. They should also be technically and economically suitable for large scale implementation in a LMIC context, as there are over 50,000 buildings in 10,155 school compounds in Sri Lanka.

Fig 3: RC-MI school buildings with irregularities.

3 Seismic retrofitting options

In order to alleviate the identified vulnerabilities of OGS (e.g. short columns and MI irregularity), three basic retrofitting solutions are considered, generating seven options (O1 to O7) through their mutual combinations. The retrofitting options considered are schematically shown in Fig 4. Option O1 was considered to eliminate the soft-storey mechanisms by adding MI walls to OGS frames (and reducing the plan and vertical irregularities in the buildings), whereas Option O2 comprises the modification of the existing MI configurations to central window (CW) only. The CW-MI intervention is preferred (as compared to partial MI in the frame), as it minimises the short column effects (with no opening being adjacent to the columns) and reduces the axial thrust induced by the MI (because of the central opening and reduced wall area).

Option O3 and O4 are considered to improve the flexural/shear capacities of the ground floor columns. Previous studies by the authors have revealed that these buildings are prone to fail through a mechanism at the ground storey (Sathurshan et al. 2023b); therefore, jacketing only the ground storey columns is selected as one of the retrofitting options. In Option O3, 100% of the GF columns are jacketed as shown in Fig 4(c). Alternatively, in Option O4, only 50% of the GF columns are jacketed, i.e. every alternate column at the GF. The RC column jacketing configuration is determined using ACI 562 (2019), and the reinforcement detail used is shown in Fig 4. It should be mentioned that the reinforcement details provided are computed based on the base shear forces acting on the columns. It is found that the additional reinforcement required to achieve the enhanced strength is less than the minimum jacketing reinforcement detailing specified in ACI 562 (2019). Hence, the latter detailing is used. Option O5 comprises a combination of options O1 and O3. Option O6 consists of applying RC jackets to all columns, and can be seen as an extension of option O3. Option O7 is a combination of options O1 and O6. Other commonly explored retrofitting options such as adding shear walls, using steel bracings, CFRP jacketing and base isolation techniques are not considered in this study (Pohoryles et al. 2019; Falcone et al. 2019). These retrofit options are not deemed to be practically feasible or economical for the low- to moderate-seismic hazard in Sri Lanka.

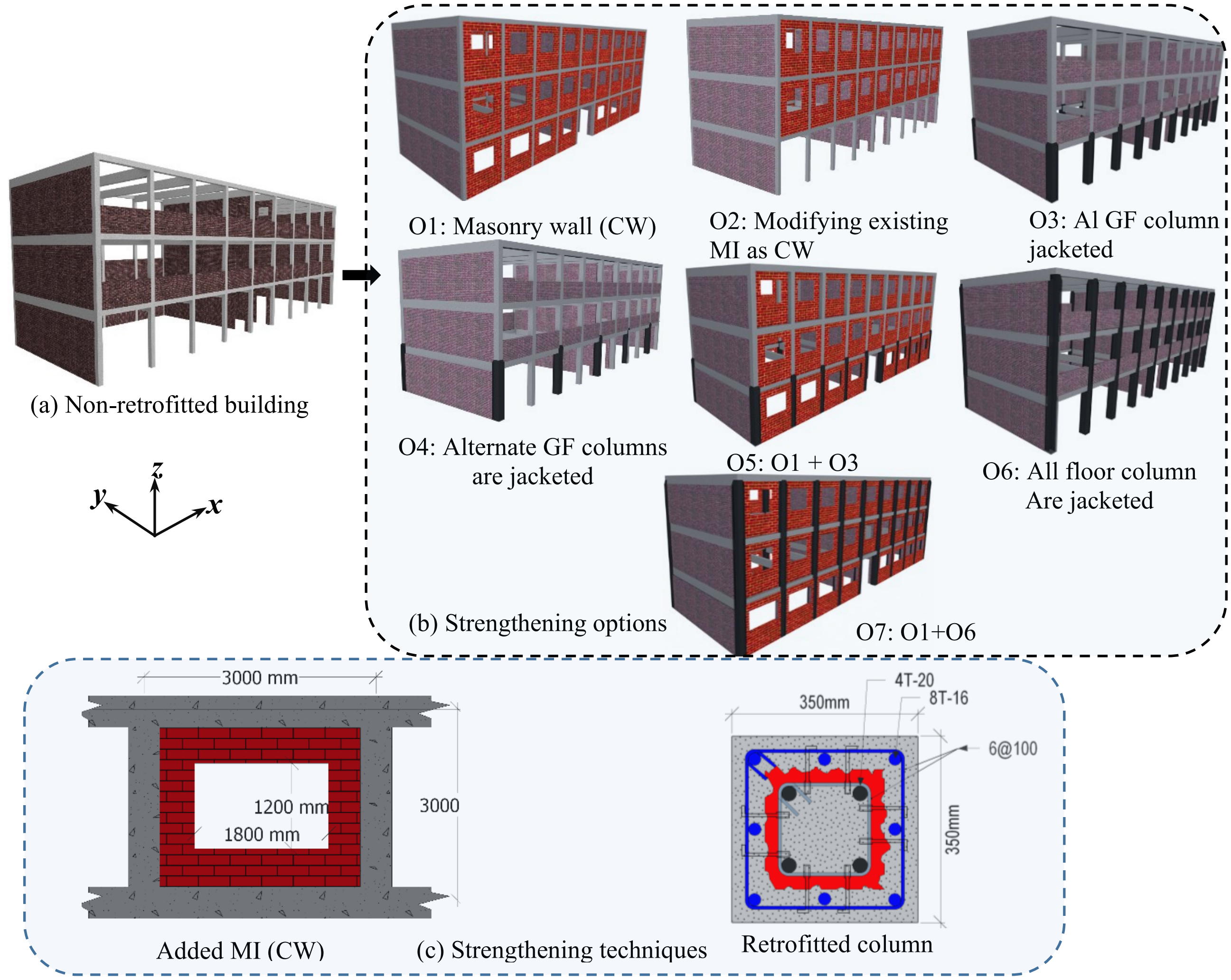


Fig 4. Seismic retrofitting options deliberated (a) non-retrofitted building (b) Strengthening options (O1, O2, O3, O4, O5, O6 and O7 and (c) Strengthening techniques

The main retrofit objective in all these cases is to achieve repairable damage to the school buildings (i.e. RC frame) under seismic excitation consistent with a return period of 475 years. However, the failure of non-structural elements (i.e. MIs) is allowed. The seismic performances of the RC-MI school buildings with and without retrofit are evaluated by using a numerical approach, the details of which are provided in next section.

4 Numerical modelling and seismic performances

The numerical method adopted to assess the seismic performances of the MI-RC school buildings was developed by the authors and presented in Sathurshan et al. (2023b). Herein, the method is extended to analyse the seismic performances of retrofitted MI-RC buildings. For the sake of clarity, a brief description of the numerical modelling method is summarised in following next.

4.1 Numerical modelling method

Numerical models of MI-RC school buildings are created and analysed through nonlinear pushover analysis by using the software OpenSees (OS) (Mazzoni et al. 2006). The RC elements (i.e., beams and columns) are represented by force-based nonlinear beam-column elements. Joints are modeled by concurrent nodes. In all the buildings analysed, a slab thickness of 150 mm is maintained, and the slab elements are modelled as rigid diaphragms. The constitutive behaviour of concrete and steel are represented by *Concrete04* and *Steel01* material models respectively, available in the OS (Mazzoni et al. 2006) library. The MIs are represented as single equivalent diagonal struts according to FEMA-356 (2000). The RC sections and detailing are provided in Fig 2 and material properties used are given in Table 1. These material properties were taken from the previous studies conducted on the Sri Lankan school buildings (Sathurshan et al. (2023a, b)).

The presence of irregularly placed MIs and openings means, that the RC buildings are prone to torsional effects, and RC elements in the building, particularly the columns, subjected to high shear forces. Being lightly reinforced buildings designed only for gravity loads, the school building columns can fail through shear (due to only nominal shear links provided and hence limited confinement in the columns). However, force-based nonlinear beam-column elements in OS (Mazzoni et al. 2006) do not account for axial-flexural-shear interaction formulations. Therefore, to capture this failure mechanism, a practice-oriented simplified method is adopted in this study, wherein the OS (Mazzoni et al. 2006) output data is post processed and the pushover curves iteratively corrected to cut-off at the shear failure of the columns. For this purpose, the section capacities determined through the sectional analysis tool Response-2000 (Bentz 2001) were integrated within the OS output data, and shear failure points determined. In other words, the shear strength obtained from Response-2000 (Bentz 2001) was compared with the shear forces from the pushover analysis in every step of the analysis; and if the shear strength of the section was less than the shear force demand, it was considered that the column would fail due to shear, before its flexural capacity. The process was carried out for both non-retrofitted and retrofitted columns, and implemented in each column of the building analysed. Further details of this procedure can be found in Sathurshan et al. (2023a, b). This approach of accounting for the shear failure of the columns is similar to the practice-oriented shear failure evaluation methods suggested for lightly MI-RC buildings by Cavaleri et al. (2017) and Celarec and Dolsek (2013).

Table 1. Mechanical properties considered in the OS models, Sathurshan et al. (2023a, b)

Constituent materials in the building		
Material	**Properties**	**Values**
Unconfined Concrete	Compressive strength (f_c)	20.0 MPa
	Peak strain (ε_c)	0.0025
	Modulus of Elasticity (E_c)	22000 MPa
Confined Concrete	Compressive strength (f_{cc})	22.0 MPa
	Peak strain (ε_{cc})	0.003
	Modulus of Elasticity (E_{cc})	24500 MPa
Steel	Yield Strength (f_y)	460 MPa
	Hardening Ratio (b)	0.001
	Modulus of Elasticity (E_s)	200000 MPa
Masonry	Compressive Strength (f_m)	1.5 MPa
	Strain (ε_{mp})	0.003
	Modulus of Elasticity (E_m)	2000 MPa

Different methods have been defined to verify the attainment of seismic damage limit states of structures in the past (Hill and Rossetto 2008). In this study, three damage limit states are defined according to the failure sequences of the non-retrofitted and retrofitted MI-RC school buildings analysed: they are (1) Damage Limitation (DL), (2) Significant Damage (SD), and (3) Near Collapse (NC). The DL state is achieved at the initiation of MI cracking, which was considered as the cracking load measured in the MI (70% of the peak load carrying capacity). The SD state is defined as the failure of MIs (at the peak load carrying capacity) and minor repairable cracks on the RC elements. Achievement of the SD damage state is the objective of the retrofitting conducted. The NC state is defined either by the development of plastic hinges (PH) in more than 50% of the GF columns, or the occurrence of shear failure in more than 50% of the GF columns, whichever happens first. The damage states are determined from the observed behavior of each structure in the non-linear pushover analysis, which is also used to define damage state threshold values of roof drift ratio (DR). The seismic performance of the non-retrofitted and retrofitted buildings are verified through the N2 method (Dolšek and Fajfar 2008). The model parameters of the buildings are obtained through eigen analysis, and the pushover curves thus transformed into capacity curves in the spectral acceleration-spectral displacement space. The 5% Acceleration-

Displacement Response Spectrum (ADRS) is calculated for each adopted ground motion - more details on the seismic hazard are given in Section 4.4. By comparing the ADRS and capacity curve of each specific building, the seismic performances of the non-retrofitted and retrofitted buildings are verified.

4.2 Seismic performance of the school buildings

The pushover curves obtained through the analyses are shown in Fig 5 in terms of base shear coefficient and roof drift ratio (DR) of the existing and retrofitted building cases. It is noted that there are slight changes in the masses of the buildings with the retrofitting solutions adopted. The attainment of damage limits (i.e. DL, SD and NC) are marked in the pushover curves presented. A limited ductility is observed in the pushover curves presented, particularly for the existing buildings, because the pushover curves are cut off at the shear failure of the columns, as explained in Section 4.1. It can be noted that the retrofitting options improve the lateral load carrying capacity and stiffness of the buildings, as expected. They also increase the roof drift values at which the different damage states are achieved.

4.3 Effectiveness of different retrofitting options

Table 2 presents the parameters characterising the response of each building for the different retrofitting solutions, i.e. natural period of vibration of the building corresponding to first mode (T), peak base shear (V_s), increase of V_s through the retrofit (as a ratio of the non-retrofitted case), initial stiffness (K_{in}), and drift values corresponding to the three damage states defined earlier. The analysed building cases are denoted using alpha-numeric nomenclature, where T1 represents the building type. S2 and S3 correspond to the number of storeys of the buildings analysed. O1 to O7 denote the retrofitting options considered. It can be noted that the O1 retrofitting method (i.e. altering MIs) improves the base shear capacities of both the two- (S2) and three- (S3) storey buildings by 30-44%. On the other hand, the O4 option improves these capacities by only 20%. These results imply that adding MIs to the buildings results in a higher lateral load capacity of the buildings as compared to only jacketing the ground floor columns. However, from the perspective of lateral drift capacities, the O4 retrofitted buildings show better distributions of deformations across the building than for the case of O1. For example, the drift corresponding to the near collapse damage state (NC) with the O2 retrofit option has a drift that is 26-42% higher than the existing buildings (for S2 and S3).

Table 2. Parameters determined from the pushover curves of the existing and retrofitted buildings analysed

Cases	*T (s)*	V_s *(kN)*	V_s *increase via retrofit*	K_{in} *(kN/mm)*	DR_{DL} *(%)*	DR_{SD} *(%)*	DR_{NC} *(%)*
T1-S3	0.76	1130	-	18.6	0.29	0.61	0.89
T1-S3-O1	0.67	1630	1.44	40.3	0.33	0.50	0.97
T1-S3-O2	0.74	1240	1.10	22.9	0.35	0.65	0.93
T1-S3-O3	0.63	1370	1.21	21.1	0.40	0.74	1.24
T1-S3-O4	0.60	1350	1.19	20.6	0.42	0.74	1.06
T1-S3-O5	0.54	1890	1.67	53.8	0.35	0.92	1.61
T1-S3-O6	0.53	2315	2.04	42.9	0.42	0.89	1.52
T1-S3-O7	0.52	2730	2.42	63.2	0.48	0.87	1.67
T1-S2	0.49	970	-	27.0	0.26	0.55	0.84
T1-S2-O1	0.42	1270	1.31	47.0	0.24	0.48	0.98
T1-S2-O2	0.45	1190	1.23	29.5	0.32	0.54	0.90
T1-S2-O3	0.38	1160	1.20	33.6	0.35	0.62	1.06
T1-S2-O4	0.43	1110	1.14	30.8	0.43	0.68	1.00
T1-S2-O5	0.32	1880	1.94	56.9	0.28	0.50	1.22
T1-S2-O6	0.35	1980	2.04	45.9	0.42	0.58	1.24
T1-S2-O7	0.31	2380	2.45	78.3	0.38	0.65	1.31

Jacketing the columns over the complete building height (O5) results in almost double the base shear capacity of the buildings and an increased drift response at NC of between 47-71% as compared to the existing buildings. All other retrofitting options (O2, O4, O5 and O7) are also seen to improve both the base shear and drift response of the buildings, as presented in Table 2. Since all the retrofitting methods are shown to improve the seismic performance of the MI-RC buildings, the most suitable retrofitting option for each building type should be selected from the best combination of engineering parameters achieved, but also from economic considerations.

4.4 Evaluation of seismic capacities

To verify the seismic capacities of non-retrofitted and retrofitted buildings against demand, the N2 (Dolšek and Fajfar 2008) method is used. For this purpose, the elastic spectra developed for the North-Western region of Sri Lanka by Dananjaya et al. (2020) were used, where the PGA of 0.35 g is taken for the return period of 475 years, being the largest PGA recommended for the country as a whole (Uduweriya et al. 2020). Ground type C (dense or medium dense sand) and importance class III are assumed as per EN 1998-1-1 (2004) to compute the seismic demand in the region. The assumption of type C (dense or medium dense sand) soil condition corresponds to the soil type commonly found in North-Western region of Sri Lanka (which is a coastal region). To perform the N2 method, reduction ($R\mu$) and ductility (μ) factors are computed specific to the buildings analysed, and the inelastic demands for the buildings obtained. Figs. 5 (b) and (d) illustrate the application of the N2 method using the bilinear idealization of capacity curves. It can be noted that the seismic capacities of existing RC-MI buildings (two and three storey) do not meet the seismic demand in the region.

It is clear that the existing school buildings fail to meet the required performance standards for maximum ductility (1.15), indicating their incapacity to withstand the expected seismic demand. It is also clear from Fig 5 that the investigated retrofitting options can help the schools achieve the required seismic demand, with repairable damage (i.e. SD), which is the objective of the retrofitting in this study. It is observed that retrofitting options O2 and O3 achieve the SD damage state, which corresponds to the attainment of MI failure, with minor repairable cracks on the RC elements. Hence, it can be said that these retrofitting options comply with the objective set initially. Some other retrofitting options (O4 to O7) attain the DL state for the demand, which implies that these retrofitting options are over-conservative and may not be economical. These aspects (i.e. attainment of excessive capacities compared to demand) have been dealt with in the MCDM analyses used in this study (as explained in Section 5).

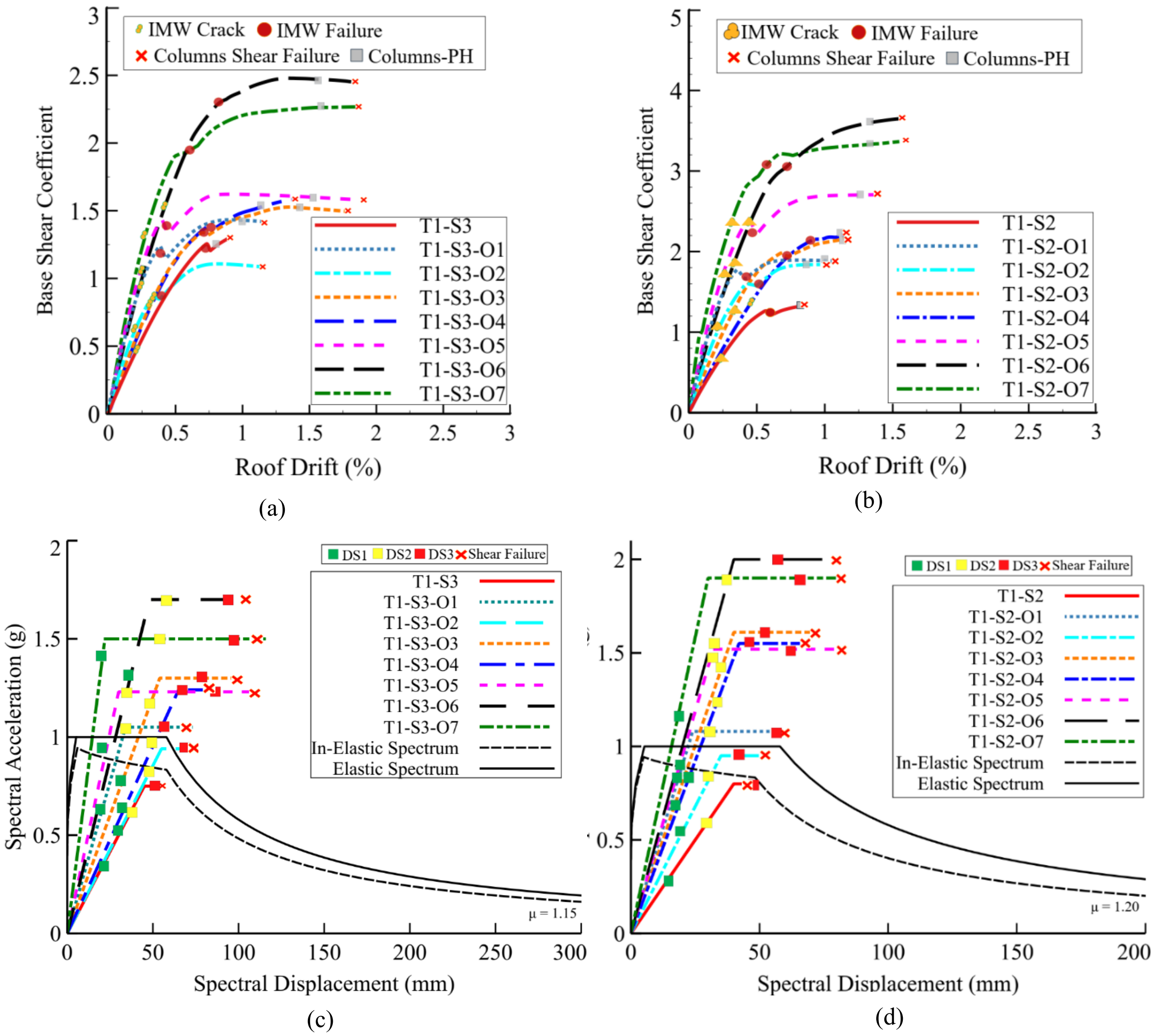


Fig 5. (a) Pushover curves of T1-S3 buildings, (b) Pushover curves of T1-S2 buildings, (c) T1-S3 capacity measurements according to N2 method (b) T1-S3, (d) T1-S2 capacity measurements according to N2 method

Various engineering parameters contribute to the seismic performance of the school buildings. In this study, the peak base shear and damage limits corresponding to DL, SD and NC were considered to be the critical engineering parameters to verify the effectiveness of retrofitting solutions. Also, the whole purpose of retrofitting these buildings was to achieve repairable structural damages; therefore, the attainment of DL and SD states have been considered as two other parameters for judging the effectiveness of the retrofitting options. It could be noted from Table 2 that these engineering parameters are attained differently with the retrofitting options, and also change with the number of storeys considered (S3 and S2). Also, some of the retrofitting options provide building capacities significantly greater than demand, making them safer options, but probably not economical (e.g. O4 to O7). Thus, since it is not possible to select the most suitable retrofitting based only on these parameters, MCDM was used in this study to select the most suitable retrofitting options for these typical MI-RC buildings.

5 Selection of optimum retrofitting option

All the retrofitting options considered have improved the seismic performances in terms of lateral load and deformation capacities. However, the optimum retrofitting option should not only depend on structural benefits, but also be based on economic factors such as initial cost, maintenance cost, and disruption of use due to retrofitting the school buildings. For this purpose, the MCDM method is used in this study, the benefits of which were highlighted in Section 1. The details of incorporating the MCDM method into study are given in the following sub-sections.

5.1 Multi-criteria decision-making method

The MCDM method enables the comparison of a set of options when a decision has to be made from multiple criteria. This method was introduced in management decision making, and later used in various engineering applications. A number of past studies have used this method to suggest the most suitable retrofitting option for their building configurations (Gentile and Galasso 2021; Clemett et al. 2022). In this study, the MCDM method is used to compare retrofitting methods for the MI-RC school buildings considered, in the context of low- to moderate-seismicity, and also economic criteria relevant to Sri Lanka. Fig 6 provides an overview of the MCDM methodology employed for ranking the available options. In order to effectively assess the options and take into account the various considerations associated with the criteria, two widely recognized techniques, namely the Analytic Hierarchy Process (AHP) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), are selected and further described below. Finally, a sensitivity analysis is carried out to validate the choice of optimum retrofitting options for Sri Lankan MI-RC school buildings.

Six criteria are considered for inclusion in the MCDM analyses. The first three criteria are based on economic considerations such as initial cost (*C1*), maintenance cost (*C2*), and retrofitting duration (*C3*). The other three criteria involve engineering parameters (lateral capacity, attainment of damage limitation, and significant damage states); they are directly obtained from the seismic performance analyses in Section 4.4. Among them, the lateral capacity (indirectly as base shear coefficient) of the retrofitted buildings was considered as criterion *C4*. This was included since the stakeholders perceive the effectiveness of retrofitting of buildings in terms of lateral strength capacities of the buildings (which is explained more in Section 5.2). The other two engineering parameters are set as the attainment of damage limitation (*C5*) and significant damage (*C6*) states, since the objective of the retrofitting was to achieve repairable damages to the buildings considered. The relative importance for each criterion is assigned using the Analytic Hierarchy Process (AHP), with pairwise comparisons being made through an expert opinion survey (see Section 5.2). Then, based on the expert opinion, weights are assigned to the criteria considered and the MCDM method used to determine the best retrofitting option for each existing building case considered.

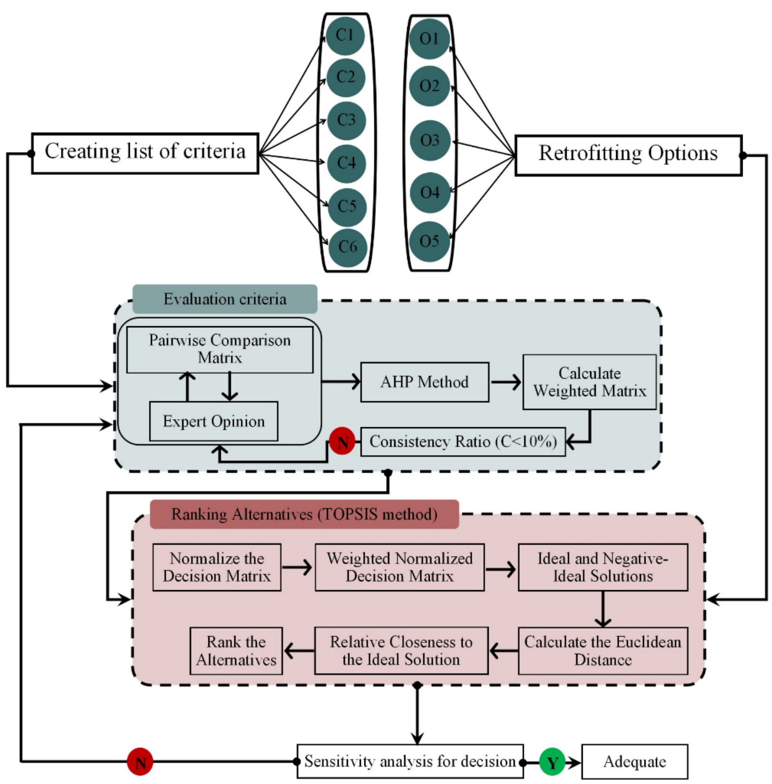


Fig 6: Overview of the MCDM method

5.2 Valuation of the criteria C_1 to C_6

The criteria selected for use in the MCDM analyses are given values based on economic factors, and engineering parameters derived from the seismic analyses. They are listed in Table 3 and explained in detail below:

- **Initial cost (C_1):** The computation of initial cost is based on the estimation of the possible expenses incurred during the retrofitting process such as demolition, material procurement, labour charges, and finishing cost, with allowance for operational cost (BSR 2023). The cost components of the retrofitting items were taken from the Building Schedule Rate (BSR 2023) updated by the Department of Buildings, Sri Lanka. Furthermore, a contingency of 10% is also included in calculating the initial cost, which is a standard practice in estimating the cost of construction projects in Sri Lanka.
- **Maintenance cost (C_2)**: Evaluation of the cost of maintenance for a retrofitted school buildings is a complex task, because of the lack of established maintenance benchmarks, particularly in Sri Lanka. Therefore, the approach used in Caterino et al. (2008), and Gentile and Galasso (2021) are adopted in this study. For all the retrofitting options considered, a mandatory inspection and potential repair of cracks/repainting every ten years is taken into account as a part of maintenance requirement. The service life of the retrofitted building is assumed to be 50 years. For alternative options involving the alteration of MIs (O1/O2/O5/O7), inspection of walls (to check the crack development) along with the maintenance of other components of the building are considered. For options involving RC jacketing of the columns (O3/O4/O5/O6/O7), inspection of the buildings at 5-year intervals are considered, and the associated cost estimated.
- **Retrofitting duration (C_3):** The total time required for a retrofitting is computed based on the retrofitting operations involved, from initial (partial) demolition to completion. It is assumed that the construction crew for altering MIs (O1) comprises an engineer, a site supervisor, two masons, and four unskilled workers. The construction crew for the RC jacketing works (O3) replicates that for O1, but additionally comprises four skilled workers. The overall retrofitting durations are calculated on the assumption that a working day consists of eight hours. In the retrofitting options O2, O4, O5, O6 and O7, the crew numbers mentioned for O1 and O2 are combined for the retrofit duration calculation.

- **Base shear coefficient (C_4), damage limitation (DL) (C_5) and significant damage (SD) (C_6)**: The lateral capacities achieved through different retrofitting methods are based on the peak base shear coefficients obtained. These values are directly taken from Table 2 and used in the evaluation. For the C5 and C6 criteria, the drift values are determined corresponding to DL and SD respectively. The values for C4, C5 and C6 in Table 3 are given as inverse values, such that higher values for these are deemed better. However, direct values are used for C1, C2 and C3, since lower values are deemed better. This is in the context of the MCDM method being set up as a "minimization" exercise.

Table 3. Decision matrix (D)

	C1 ($)	C2 ($)	C3 (days)	C4	C5	C6
T1-S3-O1	2749	326	12	0.699	0.0350	0.0189
T1-S3-O2	2458	296	10	0.757	0.0357	0.0208
T1-S3-O3	4437	521	25	0.654	0.0305	0.0168
T1-S3-O4	2445	257	13	0.648	0.0313	0.0182
T1-S3-O5	7186	647	37	0.617	0.0340	0.0133
T1-S3-O6	13461	963	76	0.405	0.0289	0.0144
T1-S3-O7	16211	1099	88	0.440	0.0249	0.0130
T1-S2-O1	1817	126	8	0.523	0.0646	0.0339
T1-S2-O2	1511	100	6	0.543	0.0626	0.0333
T1-S2-O3	4437	521	25	0.455	0.0606	0.0373
T1-S2-O4	2445	257	13	0.516	0.0556	0.0313
T1-S2-O5	6254	565	33	0.370	0.0727	0.0418
T1-S2-O6	8949	641	52	0.270	0.0606	0.0398
T1-S2-O7	10766	730	60	0.296	0.0521	0.0336

5.3 Expert survey

Expert opinion was sought to appropriately assign weights to the pairwise comparisons between the criteria considered. For this purpose, a questionnaire was prepared to determine the weights for pairwise comparisons between the criteria used, and is presented in ***Appendix A (in Supplementary Material)***. The first part of the questionnaire seeks general information of the respondents, while the second part contains the pairwise comparisons. Initially, 47 experts were invited to take part in the questionnaire survey, and 23 responded to the invitation. Expert opinion was sought from (i) engineers in charge of maintaining school buildings (from schoolworks divisions under the Ministry of Education, and Department of Buildings in Sri Lanka), (ii) engineers working in building retrofitting companies, (iii) structural engineers and (iv) academics working in similar areas.

Fig 7 shows the general information (job category, level of experience, direct relevancy in dealing with school buildings in Sri Lanka and qualification) of the experts that responded. Most of the respondents (73%) have direct experience in designing, constructing and maintaining school buildings in Sri Lanka. Fourteen questions are specifically meant to assess the pairwise comparisons between the criteria. A Likert scale is used to assess the pairwise comparisons in the questionnaire, varying from -4 to 4, where the median (i.e. 0) represents equal importance between the criteria compared; while -4 and 4 are the two extreme preferences for the criteria compared. For example, in a question given to rate the importance of initial cost of retrofitting against the maintenance cost of retrofitting in the Likert scale of -4 to 4, the selection of -4 implies that initial cost is extremely important in comparison to maintenance cost for a particular respondent; and vice-versa if 4 is selected. Anything in between -4 to 0 or 0 to 4 (-3, -2, -1, 1, 2, 3, and 3) are considered as being on a spectrum between equal and extreme importance (i.e. equal, moderate, and strong importance). Experts were asked to give their comparative preferences, using the above linguistic labels, for fourteen pairwise comparisons.

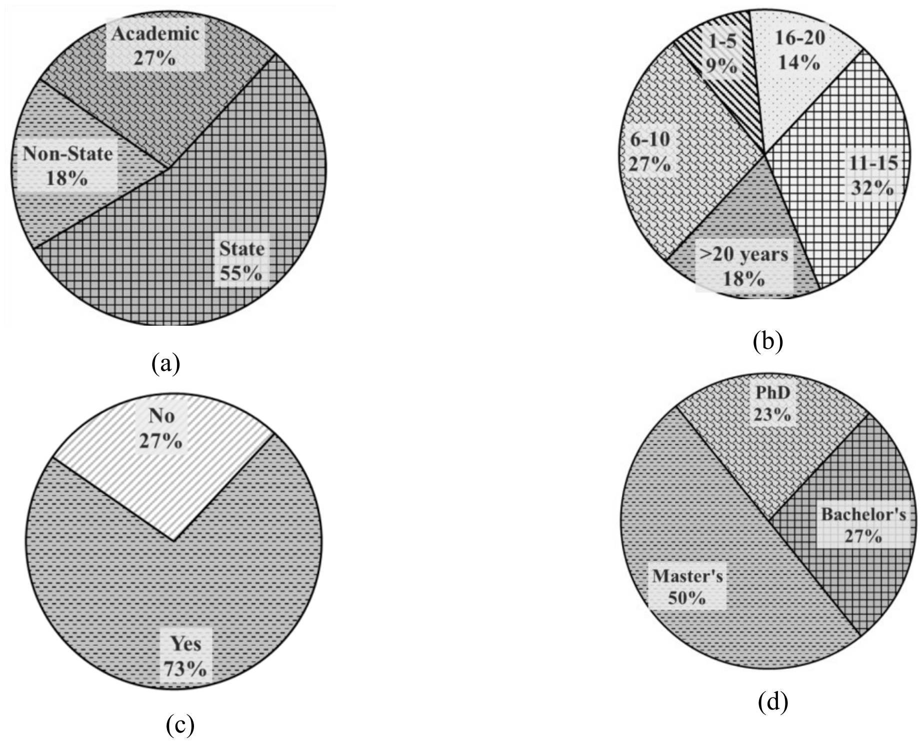


Fig 7: Details of the experts that responded to the questionnaire (a) job category (b) level of experience (c) involvements in designing school buildings and (d) highest educational qualification.

Since three of the criteria involve engineering parameters in designing retrofitting solutions (lateral capacity, damage limitation and significant damage), specific questions were asked to give pairwise comparisons between these and other economic criteria. For example, a question was asked to rate the importance of initial cost of retrofitting against achieving the required lateral capacity. Similarly, a question was asked to rate the importance of retrofitting duration against not exceeding the minor damage to the building when subjected to seismic hazards (i.e. the DL state). Likewise, set of pairwise comparison questions were asked of the experts to rate each criterion pairwise against all others to selecting the best retrofitting option for the school buildings in Sri Lanka.

Fig 8 shows the summary of the responses received from the experts. The responses are grouped into three categories, namely the equal importance response and those on either side of it, when comparing (pairwise) criteria C1 to C6. The lower part of each bar corresponds to the priority for the first mentioned criterion of the criteria pairs depicted on the x-axis. It can be noted from Fig 8, that (for C1 vs C2), nearly 77% of respondents stated that the initial cost (C1) is more important than the maintenance cost (C2), while only 5% indicated the reverse. All experts (100%) concurred that the lateral capacity (C4) is more important in retrofitting than the maintenance cost (C2). Likewise, it can be seen that the experts give higher preferences to lateral load capacity (C4) and damage limit state of the building (C5 and C6), compared to the other criteria considered. Of these engineering parameters, the lateral load capacity (C3) is seen to be more important than the damage states for the experts (C5 and C6). Experts assign less importance to the retrofitting duration (C3) than other criteria considered. For example, when comparing retrofitting duration (C3) to building damage levels (C5 and C6), 73% expressed that the retrofitted building damage levels are more important than retrofitting duration. Initial cost (C1) however, receives equal or higher priority compared to the engineering parameters, namely lateral load capacity (C4) and damage limitation (C5 and C6). The preferences obtained through the Likert scale questionnaire survey are converted to quantifiable weights as per the AHP method, as stipulated in Saaty (1987). The final weights derived from the pairwise comparisons are given in Table 4 and later used in the MCDM analyses to select the most suitable retrofitting method for the school building cases analysed.

Table 4. Scale of relative importance, after Saaty (1987).

Likert scale in questionnaire	Definition	Weights
0	Equal importance	1
-1 or 1	Moderate importance	1/3 or 3
-2 or 2	Essential importance	1/5 or 5
-3 or 3	Strong importance	1/7 or 7
-4 or 4	Extreme importance	1/9 or 9

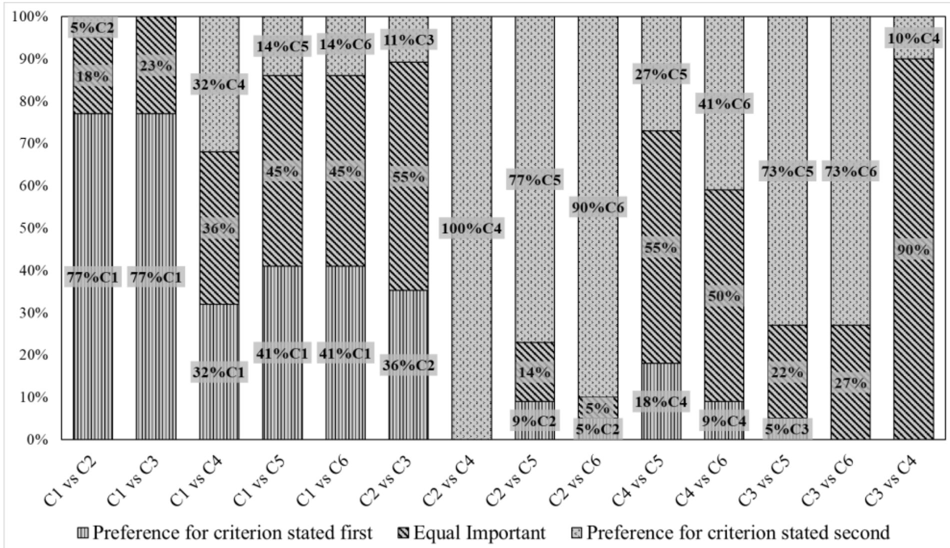


Fig 8: Summary of the experts responded to the questionnaire with different criteria (C1- initial cost, C2- maintenance cost, C3- retrofitting duration, C4- lateral load capacity, C5- attainment of DL state and C6- attainment of SD state).

5.4 Formation of weight matrix

A matrix is formed comprising the weights of the criteria, based on the expert opinion obtained, and presented in Table 5. It is important to note that the overall consistency of the matrix is assessed by determining the maximum eigenvalue (λ_{max}), which is found to be 5.229. In an ideal scenario, where the pairwise comparisons are perfectly consistent, the value of λ would be 6, hence this value is considered acceptable. To further evaluate the consistency of the pairwise comparison, a consistency ratio (*CR*) is computed, and determined to be 3.47%. A *CR* value less than 10% indicates that the pairwise comparison is consistent across the criteria considered (Saaty, 1987).

Table 5. Selected MCDM criteria and the determined weights (λ_{max} = 5.229, CR = 3.47%)

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	4.6	6.9	1.6	1.2	1.4	0.266
Maintenance cost (C2)	0.2	1.0	1.5	0.1	0.2	0.2	0.043
Retrofitting duration (C3)	0.2	0.7	1.0	0.2	0.2	0.2	0.041
Lateral capacity (C4)	0.6	7.2	6.4	1.0	0.6	0.9	0.204
Damage limitation (C5)	0.9	5.3	4.3	1.6	1.0	0.6	0.212
Significant damage (C6)	0.7	6.2	4.7	1.2	1.6	1.0	0.235

5.5 *Ranking of retrofitting options*

In order to identify the most suitable retrofitting option from the group of seven (O1-O7), the MCDM technique is applied in the final step of the procedure. The decision matrix (D), D = [x_{ij}] is formed from the parameters obtained for each option, i = {1, 2…, 7} and criterion, j = {1, 2…, 6}. It is important that all the values of x_{ij} are included in the decision matrix as the initial input for the TOPSIS method (Yoon and Hwang 1981). Then the decision matrix (*D*) has to be normalized (linearly, and each criterion separately), in order to make consistent comparisons. Eq-1 is used to perform the TOPSIS procedure to evaluate the r_{ij}.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{1=1}^{7} x_{ij}^2}} \qquad \text{(Eq-1)}$$

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 Fig 9, with the x_{ij} matrix being normalized as $R = [r_{ij}]$. Subsequently, the weighted normalized matrix V can be calculated by multiplying the R with weight corresponding to j^{th} column (i.e. j^{th} criterion), such that $V = [w_j \times r_{ij} = v_{ij}]$. The ranking of the retrofitting options can then be determined.

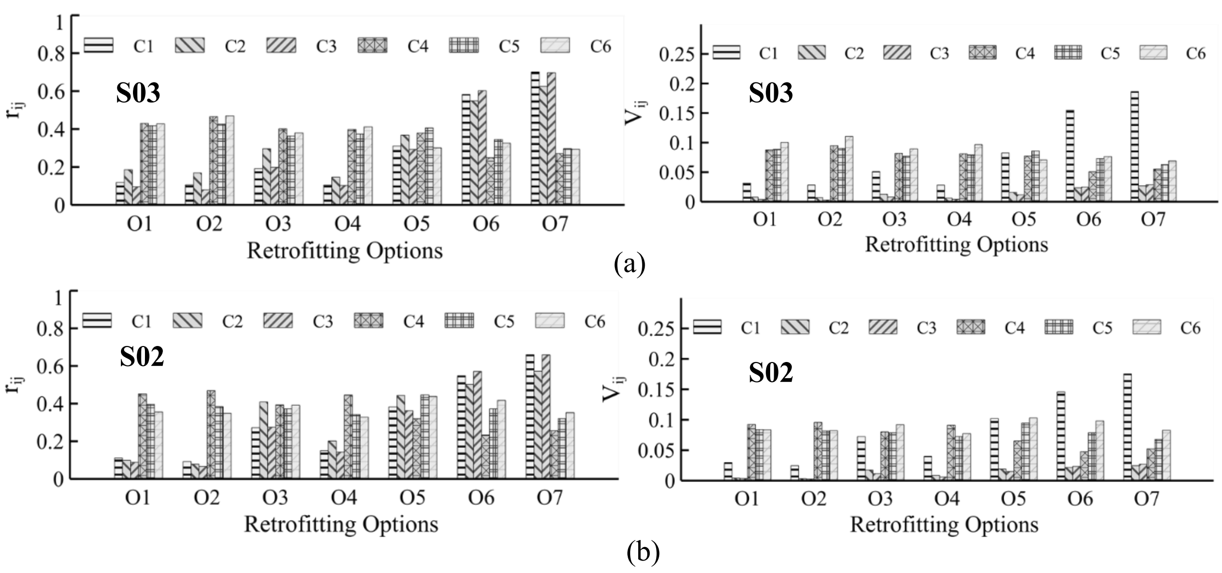


Fig 9: (a) Normalised performance (r_{ij}) for S3 and S2 and (b) weighted normalised performance (V_{ij}) for S3 and S2 with respect to comparison among options and criteria.

The MCDM method employs a six-dimensional space (one for each criterion) to represent each option (O1-O7) and the fictitious alternatives ($O*$ and O-), where the performance of each option along the C1-C6 criteria is mapped onto the respective axes. Table 6 shows the relative closeness of each option for the S2 and S3 buildings adopted in the study, where S_i* and S_{i-} and are the distances of the options O_i (i = {1, 2...,7}) to $O*$ and O- respectively. These are calculated using Eqs 2 to 4:

$$S_{i*} = \sqrt{\sum_{j=1}^{6}\left(v_{ij} - v_{j*}\right)^2} \quad \text{(Eq-2)}$$

$$S_{i-} = \sqrt{\sum_{j=1}^{6}\left(v_{ij} - v_{j-}\right)^2} \quad \text{(Eq-3)}$$

$$C_{i*} = \frac{S_{i-}}{S_{i*} + S_{i-}}; \quad \text{(Eq-4)}$$

where i= 1,2,3,4,5,6,7 *and j= 1,2,3,4,5,6*

It can be noted from the $Ci*$ values that for the S3 buildings (three-storey), option O4 ($Ci*$ = 0.787) is the best solution (shortest distance from the ideal solution and near furthest distance from the worst solution). On the other hand, for S2 (two-storey), option O1 ($Ci*$ = 0.758) is found to be the optimum retrofitting solution. However, when considering the S3 building cases, the O1 and O3 options also come close to O4, given their $Ci*$ values are 0.743 and 0.751, respectively, while for the S2 cases the $Ci*$ of the O2 and O4 are closer to the O1 than the other options. The outcome of the MCDM method can be sensitive to the criteria and their weights, as indicated by Caterino et al. (2008). Although the weights used in this paper are obtained from expert opinions, these were limited in number, and it would be instructive to investigate how the MCDM performs for varying criteria weights. Thus, in the next section, a sensitivity analysis is carried out for the criteria used in the MCDM method.

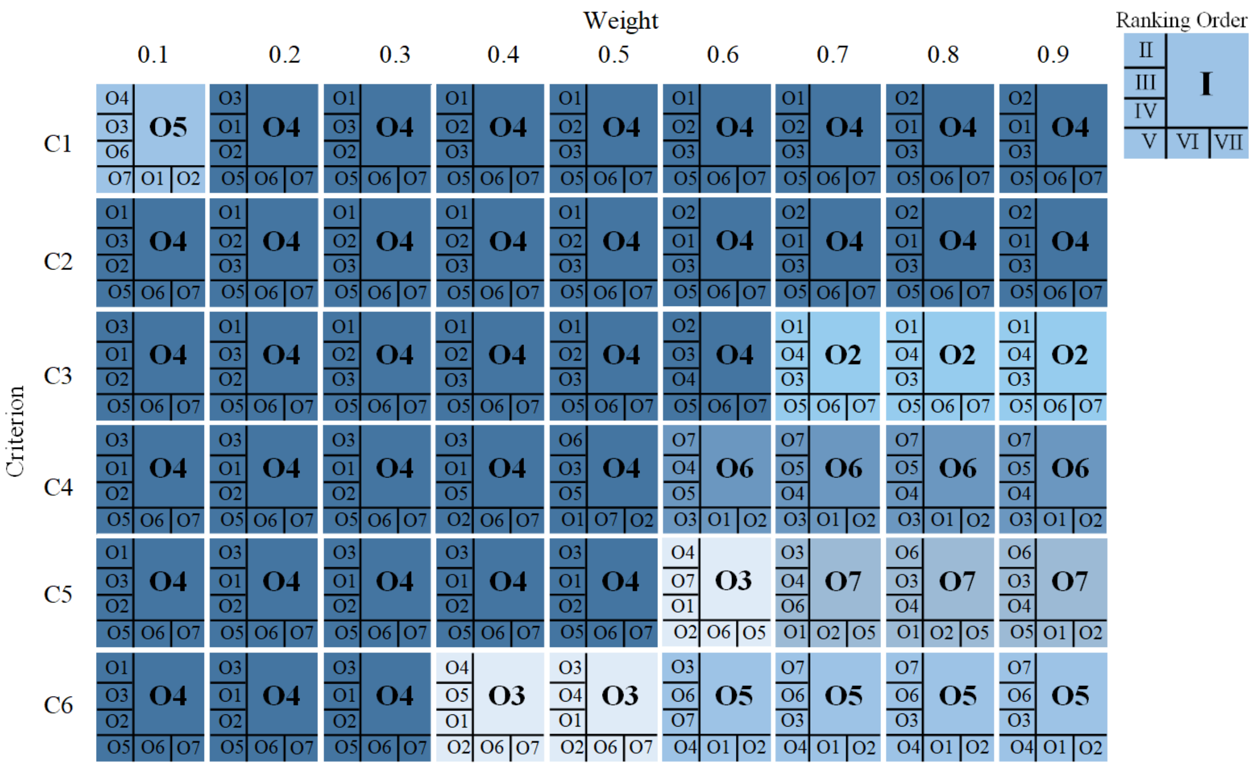
Table 6. Relative closeness to the ideal solution of retrofitting options

Options	Si-	Si*	Ci*	Options	Si-	Si*	Ci*
T1-S3-O1	0.158	0.055	0.743	T1-S2-O1	0.151	0.048	***0.758***
T1-S3-O2	0.161	0.066	0.708	T1-S2-O2	0.156	0.050	0.756
T1-S3-O3	0.140	0.047	0.751	T1-S2-O3	0.107	0.063	0.631
T1-S3-O4	0.163	0.044	***0.787***	T1-S2-O4	0.142	0.047	0.753
T1-S3-O5	0.114	0.066	0.634	T1-S2-O5	0.081	0.090	0.473
T1-S3-O6	0.067	0.130	0.338	T1-S2-O6	0.059	0.126	0.318
T1-S3-O7	0.064	0.161	0.282	T1-S2-O7	0.055	0.154	0.263

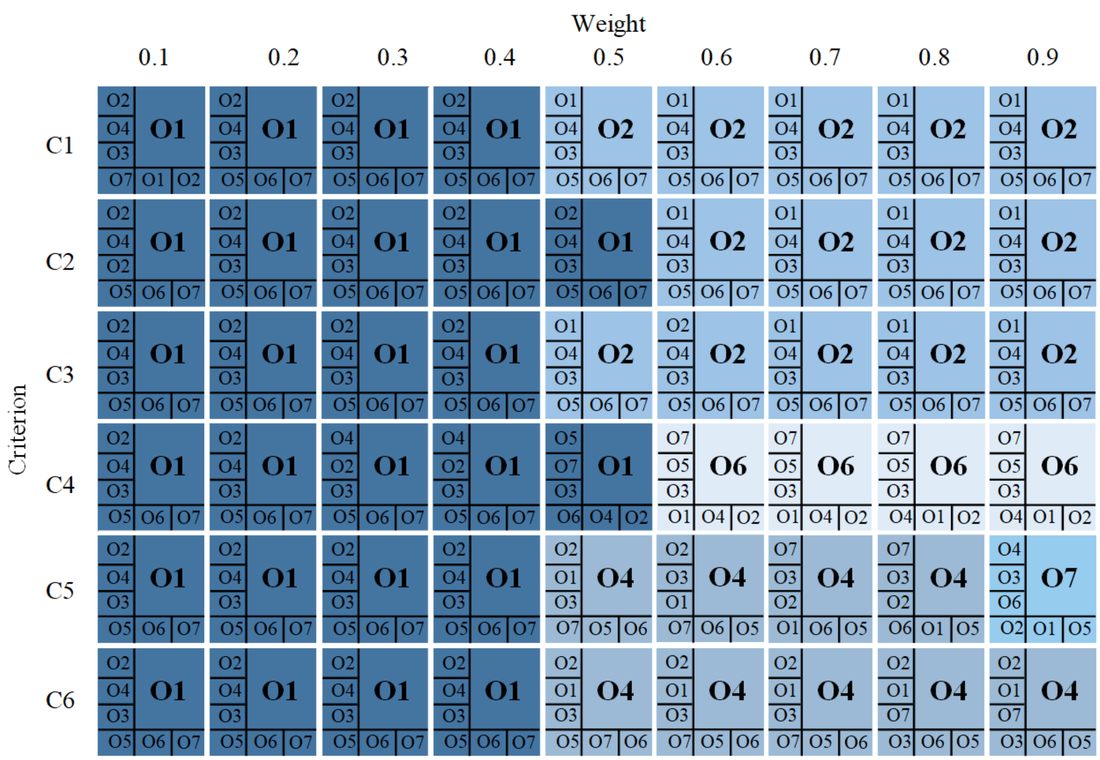
(Note: the highest number under Ci* column is the optimal option)

5.6 Sensitivity analysis

In order to verify the appropriateness of using MCDM and the selected best retrofitting option, a sensitivity analysis is carried to evaluate the stability of the recommended options. In the sensitivity analysis, each weight is varied from 0.1 to 0.9 and the outcomes, in terms of optimum retrofitting option and the ranking of other options, are compared. It is important to note that when the weight for a particular criterion is changed, the weights assigned to the other criteria are proportioned to ensure that the sum of the weights remains equal to 1.0 (as per Table 5). This proportioning of remaining criteria is assigned based on the initial proportions of the weights obtained as per Table 5. For example, if weight of the C1 criterion is set to 0.4 in the sensitivity analysis, the remaining 0.6 is distributed to other criteria based on the proportions of weights derived (they turn out to be *C2=0.04*, *C3=0.03*, *C4=0.17*, *C5=0.17*, and *C6=0.19*). In this way, it was attempted to maintain the weights derived through expert survey, while exploring the sensitivity to their variation. The results of the sensitivity analysis are presented in Fig 10 for the S2 and S3 MI-RC school buildings investigated. The legend to Fig 10 explains the ranking order of options (I to VII) for each case.



(a)



(b)

Fig 10: Sensitivity analysis (a) three storey building and (b) two storey building

Fig 10(a) shows the optimal solutions for different criterion weights in the context of three storey school buildings, and reveals that option O4 emerges as the dominant outcome for the optimum retrofitting solution, despite the weights assigned being varied from 0.1 to 0.9, representing nearly 67% of Fig 10 (a). Moreover, the difference in relative closeness between O4 and other options are significant (Table 6), further supporting the conclusion that O4 is the optimum retrofitting solution for S3. For S2 school buildings (Fig 10(b)), O1 proves to be the optimum retrofitting solution, with nearly 50% of the cases analysed implying that this retrofitting option is the most suitable. Overall, the sensitivity analysis corroborates the findings obtained in Section 5.5, where the preferred retrofitting options for three-storey and two-storey buildings are identified as O4 and O1 respectively. Also, the sensitivity analysis implies that the MCDM method is quite versatile when multiple criteria contribute to the final decision-making.

6 Summary and conclusions

This study contributes to the knowledge on developing retrofitting schemes for MI-RC school buildings in low- to moderate-seismic regions, while incorporating the economic constraints prevalent in developing countries. In this study, the most suitable seismic retrofitting options for MI-RC school buildings in Sri Lanka (where some parts of the country are subject to moderate seismicity) are numerically examined. Three main retrofitting options (adding/altering MIs, RC jacketing of columns and their combinations) are considered, resulting in seven different retrofitting solutions. All the retrofitting options considered are seen to improve the seismic performance of both building types (S2 and S3), in terms of lateral load capacity as well as roof drift at the damage states considered. The MCDM method is then used in this study to find out which of the retrofitting options is optimal considering both engineering (lateral capacities and damage limits) and economic parameters for the Sri Lankan context. Expert opinions are sought to appropriately rank the criteria considered in the MCDM.

The overall analyses reveal that the O4 option (i.e. jacketing 50% of the columns only on the ground storey) is the optimum retrofitting option for the three storey (S3) MI-RC school building case. For the two storey (S2) MI-RC school building with the same typology, the O1 (i.e. adding/altering MIs) is found to be the optimum retrofitting option. This implies that different retrofitting solutions are needed for different configurations of buildings. Sensitivity analyses conducted on the MCDM approach corroborate that the O4 and O1 retrofitting options are optimum for S3 and S2 school buildings respectively. The sensitivity analyses also confirmed that the rankings obtained through the expert opinion weightages were robust. The MCDM method could be effectively used to select the optimal retrofitting options in these conditions; it can also accommodate the adding of additional criteria if needed.

In conclusion, seismic performance analyses coupled with MCDM analyses are observed to be effective for identifying the most suitable retrofitting options for existing MI-RC school buildings in Sri Lanka. Also, the approach developed in this study can be extended to study school buildings in other low- to moderate-seismic regions, where minimal and cost-effective interventions can be applied to make those buildings safer. A similar approach can also be followed to evaluate suitable retrofitting solutions for other disaster critical infrastructures such as hospitals and bridges.

CRediT authorship contribution statement

Mathavanayakam Sathurshan: Conceptualization, Formal analysis, Data Curation, Writing - Original Draft, **Julian Thamboo**: Conceptualization, Supervision, Data Curation, Writing - review & editing. **Tiziana Rossetto:** Project Administration, Funding acquisition, Writing - review & editing. **Chinthaka Mallikarachchi**: Supervision, Writing - review & editing, **Kushan Wijesundara**: Supervision, Writing - review & editing. **Jonas Cels**: Formal analysis, Writing - review & editing. **Marco Baiguera:** Writing - review & editing. **Marta Del Zoppo:** Writing - review & editing. **Priyan Dias**: Project Administration, Funding acquisition, Writing - review & editing.

Conflict of interest

Authors declare no conflict of interests in the research carried out.

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