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Seismic vulnerability assessment of old churches in the twin cities of Bhubaneswar and Cuttack using the macroelemental approach

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Historic buildings are the cultural and traditional identity of a country. However, these buildings are vulnerable to earthquakes because of their aged structure, poor maintenance, and inadequate structural health monitoring. Therefore, seismic vulnerability assessment is a critical aspect in the restoration and retrofitting of heritage buildings. In this study, a comprehensive survey was performed to collect the data of old and historic church buildings in and around the twin cities of Bhubaneswar and Cuttack in Odisha for evaluating the performance of these structures against seismic activity. The macroelemental method for seismic vulnerability assessment was used to calculate the seismic vulnerability index of church buildings. The probable damage was estimated based on the obtained values of the mean damage grade according to the EMS-98 scale and were compared with the grade of damageability acquired using the rapid visual screening method for Indian conditions. Damage probability matrices were constructed to determine the probabilistic future damage. This study identified church buildings that require immediate renovation and retrofitting.

KEYWORDS

seismic vulnerability assessment, heritage structure, earthquakes, structural health monitoring, macroelemental approach, seismic retrofitting, seismic upgrading, reinforced concrete arches

1 Introduction

Conservation of historic buildings is critical for safeguarding the cultural and traditional identity of people and promoting tourism for economic growth. Historical architecture considerably influences modern construction techniques. Furthermore, the conservation of heritage structures economically boosts the country through tourism development (Feilden, 2007). Traditional methods and numerous empirical techniques that counteract local hazards can be used to construct these historic structures. However, these structures require constant attention and robust preservation methodologies to ensure their longevity in the long run (Mishra, 2021).

The seismic vulnerability of a building is the extent to which a building is susceptible to earthquakes (Aktan and Ho, 1990). Seismic vulnerability assessment refers to the calculation of the degree of susceptibility in terms of the damage estimated for future earthquakes. Uncontrollable shaking resulting from earthquakes can cause considerable damage and destruction to existing structures. Past earthquakes in India have caused considerable damage to property and life. Because earthquakes are sudden and unpredictable, appropriate conservation techniques should be followed to prevent damage to historic buildings. Several researchers have carried out case studies for seismic vulnerability calculations for various earthquake events, such as the 2003 Valle Scrivia earthquake (Ruggieri et al., 2020b), 2009 L'Aquila earthquake (De Matteis et al., 2019; Fazzi et al., 2021), 2010 Maule Chile earthquake (Palazzi et al., 2020), 2012 Emilia-Romagna earthquake (Formisano and Milani, 2019), 2017 Earthquake in Ischia Italy (Salzano et al., 2022) etc. Therefore, the evaluation of seismic vulnerability in historic buildings is critical for restoration.

1.1 Methods of seismic vulnerability assessment

Several methodologies have been developed for performing seismic vulnerability assessments of structures (Calvi et al., 2006; Alam et al., 2012; Goded et al., 2018; Shakya et al., 2018; Fabbrocino et al., 2019; Kassem et al., 2020; Aghabeigi and Farahmand-Tabar, 2021; Chieffo et al., 2021; Shabani et al., 2021). These methodologies can be classified into analytical (D'Ayala and Speranza, 2003), empirical based on macroelement approach (De Matteis et al., 2020; Sangiorgio et al., 2021b), and integrated multidisciplinary approaches (Dall'Asta et al., 2019; Grazzini et al., 2020). Analytical methods can be classified into simplified and detailed methods of vulnerability assessment (Shabani et al., 2021). The simplified methods include the collapse-mechanism-based methods proposed by Augusti et al. (2001), capacity-spectrum-based, and fully displacement-based methods, whereas the detailed methods include nonlinear static analysis (push-over analysis) (Fortunato et al., 2017; Mosoarca et al., 2019; Olivito et al., 2019), and nonlinear time history analysis (incremental dynamic analysis) (Barbieri et al., 2013; Formisano et al., 2018; Briceño et al., 2019; Mosoarca et al., 2020; Shehu, 2022). Rapid visual screening (RVS) methods and seismic vulnerability index methods proposed by Lourenço and Roque (2006) are typically used for seismic vulnerability approaches.

The RVS method was first proposed in the US in 1988 in the FEMA 154 report, and the latest updated version was released in 2015 (FEMA, 2017). Numerous RVS methods were proposed by various countries based on the local conditions (Angeletti et al., 1988, 2005; Ansal et al., 2003; Recommendations, 2006; ASCE, 2014). Arya (2011) proposed the RVS method for Indian conditions. This method was subsequently developed further by many authors (Sinha and Goyal, 2004; Jain et al., 2010).

Benedetti and Petrini (1984) were the first to propose a vulnerability index method to determine the seismic vulnerability of buildings. Vulnerability methods were developed for various types of architecture, such as churches (Ferreira et al., 2014), vernacular architecture (Ortega et al., 2019; Ortega et al., 2021) and others, by considering parameters specific to the structure. The macroelemental method is a seismic vulnerability index method developed for church buildings. In this method, the seismic vulnerability is calculated by the division of the structure into various macroelements (Lagomarsino et al., 2004). The elements that affect the seismic performance were selected, and the vulnerability index was calculated as the weighted average. Hybrid methods are a combination of both methods in which the empirical datasets of earthquake damage data and structural models of nonlinear analysis are considered (Kappos, 2016).

Sarhosis et al., 2018 estimated seismic vulnerability of masonry towers by applying both analytical and 3D-finite element analysis for sixteen representative cases with different slenderness ratios, heights, and shear areas. D'Altri et al., 2020 provided a comprehensive overview of modelling strategies for brick-masonry structures, categorising them into four groups: block-based models, continuum models, macroelement models, and geometry-based models. Based on the review, the authors pointed out that block-based models are the most accurate in capturing the mechanical response of masonry, while continuum models are the most popular for analysing masonry structures. Due to their simplicity, macro models are commonly used by practitioners. However, their lack of structural features such as interaction between several in-plane and out-of-plane damages and toothing between orthogonal walls presents certain limits to their predictions. In addition, by carrying out limit-based analysis of equilibrium states, geometry-based models can provide solutions for forecasting collapse mechanisms in brick-masonry buildings.

1.2 Case studies of seismic vulnerability assessment

This section details case studies of seismic vulnerability assessment of historic and ordinary buildings across various countries. D'ayala (2002) evaluated the seismic vulnerability of historic masonry buildings subjected to earthquakes in the Marche region in Italy based on the failure mechanism of the structures. Failure mechanism identification and vulnerability evaluation were used for assembling the earthquake damage data and the online building of the database. The possible out-of-plane modes of the collapse of the external walls were considered for the formulation. The analysis revealed the importance of the load-bearing walls in the out-of-plane collapse of the masonry walls in historic buildings.

Several seismic vulnerability studies have been conducted for Indian conditions. Rautela et al. (2015) evaluated the seismic vulnerability assessment of buildings in Nainital and Mussoorie

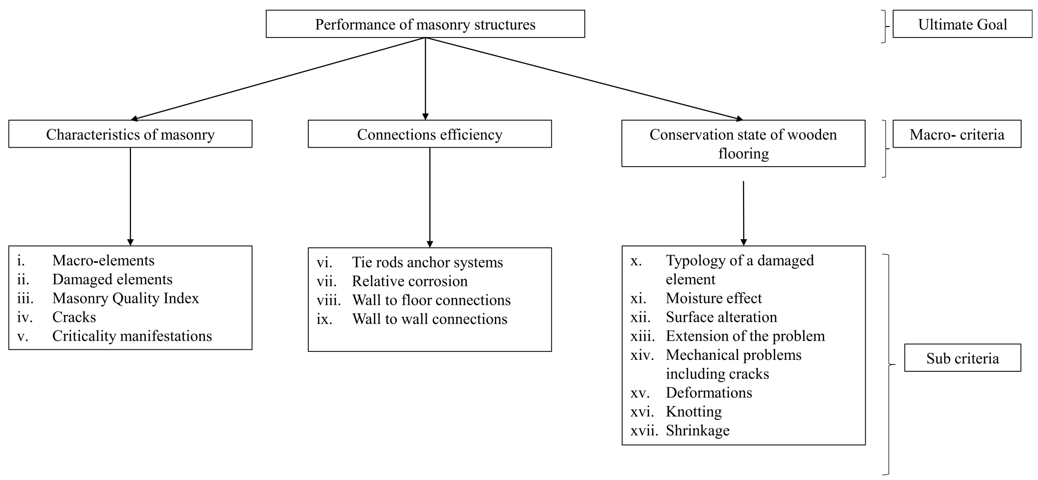

FIGURE 1
Macro criteria and subcriteria considered for AHP (Sangiorgio et al., 2021a).

in the Himalayan region of India. The RVS technique was used with the GIS and remote sensing tools, and it was followed by assigning damage grades based on the EMS-98 scale (Grünthal, 1998), that is, Grades 1 to 5. The economic loss that can be incurred was also estimated. A total of 6206 buildings were surveyed, of which 14% and 18% of the buildings in Nainital and Mussoorie, respectively, exhibited a high probability of Grade 5 damage in the case of an earthquake of intensity VII on the MSK scale. The results revealed that most healthcare infrastructure surveyed is highly vulnerable to seismic damage. Joshi et al. (2019) performed a seismic vulnerability assessment on the lifeline buildings in the Himalayan region of Uttarakhand, India, by using the RVS technique. A structural score (S) was calculated based on the basic structural hazard score and performance modification factors (PMFs). The BSF was calculated from the previous earthquake damage data and assigned based on the category of buildings, and the PMFs depend on several parameters that affect the performance of the building during an earthquake. According to this study, 72.14% and 36.14% of masonry and RC structures of damageability Grades 5 and 4 would be unable to offer services immediately after an earthquake, respectively. Inadequate maintenance and neglected engineering were the main causes of the deteriorated state of lifeline buildings. Sangiorgio et al. (2021a) proposed a novel procedure for the visual surveys of masonry buildings. This procedure involves the AHP methodology for analyzing data collected in the visual survey, a novel survey form to perform on-site rapid visual surveys, and a computerized tool created using a design support system for large-scale data acquisition. The hierarchal structure for AHP is displayed in Figure 1.

A global index, $I_{STRUCTURE}$ was calculated by calculating the average of the masonry index (I_M), connection index (I_C), and wood elements index (I_W). These indices have a value within the range of 0–10 and are calculated by considering the parameters involved in each subcriterion using the following equations. The masonry index is expressed by the following expression:

$$I_M = v_1 w_{(1,j)} + v_2 w_{(2,j)} + v_3 w_{(3,j)} w_{(3,j,k)} + v_4 w_{(4,j)} w_{(4,j,k)} + v_5 w_{(5,j)} \tag{1}$$

The connection index is expressed as follows:

$$I_C = v_6 w_{(6,j)} + .. + v_9 w_{(9,j)} w_{(9,j,k)} \tag{2}$$

The wood flooring index is obtained by using the following expression:

$$I_W = v_{10} w_{(10,j)} + .. + v_{17} w_{(17,j)} \tag{3}$$

This proposed methodology was applied to the SS. Salvatore church in Italy. An $I_{STRUCTURE}$ value of 1.52 was obtained. This value indicates low damage and excellent structural conditions. The values of I_M and I_C were more than 7 and require additional investigations.

Sarraz et al. (2015) assessed the seismic vulnerability due to a change in the code provisions of the Bangladesh National Building Code (BNBC)-2012 in the seismic design coefficient for the region for existing building stocks at Chandgaon in Chittagong city in Bangladesh. Basic structural-hazard and performance scores were calculated using the RVS technique and Indian evaluation methods. Vulnerability factors, such as structural irregularities and story drift parameters, were considered in the evaluation.

Perrone et al. (2015) suggested a RVS approach for determining the safety index for RC hospital buildings by assessing the parameters that influence the vulnerability of these class of buildings. Unlike previous methodologies, in this study, non-structural elements were considered. This methodology was based on questionnaires consisting of 145 parameters that can be classified into structural safety, nonstructural safety, and functional safety parameters, which carry weights of 50%, 30%, and 20%, respectively, for the calculation of the safety index. Each parameter is assigned three safety levels, namely low, medium, and high. Six indices were calculated in the safety index evaluation. Here, I_{STR} (structural elements), I_{NSTR} (nonstructural elements), and I_{ORG} (organizational aspects), were primary indices, whereas the other three indices were vulnerability (VULN), exposure (EXP), and hazard (HAZ). This method was applied to two Italian hospital buildings, and the results were validated by performing pushover analysis on the same buildings. The results of the two methods were consistent. D'Amato et al. (2019) carried out seismic risk sssessment for Matera Cathedral using different simplified methods and without carrying out complex numerical analysis. Ruggieri et al. (2020a) developed this method for assessing the seismic risk of RC school buildings in the Apulia Region (Southern Italy) to identify the buildings that require investigations and retrofitting. The safety index for the school buildings was calculated considering all parameters that can induce seismic risk. The method was applied to ten RC school buildings, representing the RC school stock. The results revealed that the high vulnerability level of the buildings could be primarily attributed to in-plan and in-elevation irregularities and inadequate structural detailing. The parameters that exhibit an increased effect on the evaluation of the safety index are I_{STR} and HAZ. The results obtained from the RVS method prove the effectiveness of the methodology when compared to the pushover analysis results.

Halder et al. (2020) evaluated the seismic vulnerability of existing unreinforced masonry (URM) buildings in the city of Agartala in North-East India. The study included the URM structures affected during the 5.7 magnitude earthquake in 2017 in Ambasa. An analytical evaluation was performed based on the nonlinear static method to develop the parameters of the bilinear capacity curve and subsequently determine fragility functions. The fragility curves obtained proved that the URM structures in Agartala were critically damaged even for an earthquake of PGA of 0.18 g. Therefore, their vulnerability was high.

2 Methodology

The macroelemental method was used to perform seismic vulnerability assessment by calculating the vulnerability index. Individual parameters or damage mechanisms that affect the seismic performance of the structure were selected, and the vulnerability index was calculated. This process is performed in three steps.

1. Assessment of possible damage mechanisms based on the presence of macro-elements.
2. Calculation of the weights of parameters and damage mechanisms using the analytical hierarchy process.
3. Calculation of the vulnerability index and mean damage grade using the formulation and comparison of damage grades with the RVS method.

TABLE 1 Possible collapse mechanisms of a typical church building (Lagomarsino et al., 2004).

Macro-elements of church building	Collapse mechanisms
Facade	Facade overturning
	Tympanum overturning
	In plane mechanisms
	Narthex
Nave	Transversal response of the nave
	Shear mechanism of lateral walls
	Longitudinal response of colonnade
	Vaults of central nave
	Aisle vaults
Transept	Transept façade overturning
	Shear mechanism in transept
	Transept vaults
Triumphal arches	Triumphal arches
Dome	Dome
	Roof lantern
Apse	Apse overturning
	Shear mechanism in apse
	Apse vaults
Roof covering	Roof of nave
	Roof of transept
	Roof of apse
Ancillary rooms	Irregular plan/elevation
Projections	Projections
Bell tower	Bell tower
Belfry	Belfry

2.1 Assessment of possible damage/collapse mechanisms

The typical set of elements of a church building and the collapse/damage mechanism involving those elements according to Lagomarsino et al. (2004) are detailed in Table 1. For possible damage/collapse mechanisms of a typical church building, please refer to research paper of Penna et al. (2019).

2.2 Analytical hierarchy process

The analytical hierarchy process is used to determine the solution to complex decision-making problems by using mathematics and psychology (Saaty, 2008). AHP provides the best solution based on the requirements of the user. This method is most suitable for calculating the weights of the parameters or criteria. The method follows the structural hierarchy from the ultimate goal at the topmost level, criteria, and subcriteria in the intermediate levels, and the available decision alternatives at the bottom level.

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TABLE 2 Saaty's ratio scale for pair-wise comparison of weights of criteria/alternatives (Saaty, 2008).

Intensity of importance	Definition
1	Equal importance between the criteria
3	One criterion is moderately important than the other one
5	Strong importance of one criterion over the other one
7	Very strong importance of one criterion over the other one
9	Extreme importance of one criterion over the other one
2, 4, 6, 8	Intermediate values between judgments
Reciprocals of the above numbers	When a second activity is compared to an activity that has one of the above numbers assigned to it, the second activity has the reciprocal value when compared to the first

TABLE 3 Values of Random index (Noble and Sanchez, 1993).

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14
R.I	0	0	0	0.49	0.82	1.03	1.16	1.25	1.31	1.36	1.39	1.42	1.46	1.48

The decision alternatives are subsequently analyzed by comparisons through pair-wise comparison matrices, which are reciprocal matrixes that contain the weights of the parameters in the structural hierarchy in terms of importance. Saaty's ratio scale for pair-wise comparison of parameter weights is presented in Table 2. The Eigenvector method is used to determine the critical weights of the parameters. The consistency of the weights was evaluated by calculating the consistency index and the consistency ratio. The consistency index formulation is as follows:

$$C.I = (\lambda_{max} - n)/(n-1) \tag{4}$$

where C.I is the consistency index, n is the order of the comparison matrix, $\lambda_{\max}$ is the largest Eigenvalue of the comparison matrix.

The consistency ratio is expressed as follows:

$$C.R = (C.I)/(R.I) \tag{5}$$

where C.R, C.I and R.I represent the consistency ratio, consistency index, and random index respectively based on n values Noble and Sanchez (1993). The values of the random index are presented in Table 3. A consistency ratio of less than 0.10 ensures that the judgments are valid. If the value of the consistency ratio is greater than 0.10, the judgments should be revised.

In the current method, the principle of AHP was used to calculate the weights of all the available criteria and alternatives. The ultimate goal is the seismic vulnerability of the church building. The possible criteria and the existing alternatives available for each criterion are selected based on the local church typologies observed in the survey of churches. The six criteria and alternatives for each and their weights are presented in Table 4. The first three criteria, that is, the type of the element, failure mechanism, and type of damage, were considered according to Uva et al. (2019) and three new criteria, namely type of roofing system, type of structure, and year of construction, were introduced. These parameters are considered based on the typology of the surveyed churches.

2.3 Macro-elemental method

The macroelemental method refers to the calculation of the seismic vulnerability of the structure by division of the structure into various macroelements. The elements that affect the seismic performance were selected, and the vulnerability index was calculated as the weighted average using the following equation (Lagomarsino et al., 2004):

$$i_v = \frac{1}{6} \times \frac{\sum_{k=1}^{28} \rho_k \times \left(v_{ki} - v_{kp}\right)}{\sum_{k=1}^{28} \rho_k} + \frac{1}{2} \tag{6}$$

where i_v is the vulnerability index; ρ_k is the weight assigned to the mechanism based on its influence on the whole structure; v_{ki} is the vulnerability score of macroelement; $v_{k\rho}$ is the seismic score of macroelement. Here, v_{ki} and $v_{k\rho}$ are assigned a value between 1 and 3 for each parameter. The value of i_v lies between 0 than 1. The value of the vulnerability score (v_{ki}) is assigned based on the presence of vulnerability indicators, such as thrusts of vaults and heavy beams, and the value of a-seismic score ($v_{k\rho}$) was assigned based on the availability of anti-seismic elements such as tie rods, buttresses, and ring beams.

The weight assigned to each mechanism is calculated using the following equation (Uva et al., 2019):

$$\rho_k = v_1 * w_{1j} + v_2 * w_{2j} + v_3 * w_{3j} + v_4 * w_{4j} + v_5 * w_{5j} + v_6 * w_{6j} \tag{7}$$

TABLE 4 Weights of selected criteria and alternatives.

Criteria (v_i)	Weight (ρ_k)	Alternatives (w_{ij})	Weight (ρ_k)
Type of the element (v1)	0.16	Primary seismic element (w11)	1
		Secondary seismic element (w12)	0.6
		Secondary structural element (w13)	0.27
		Non-structural element (w14)	0.1
Failure mechanism (v2)	0.07	Kinematic out of plane (w21)	1
		Kinematic in plane (w22)	0.65
		Not definable (w23)	0.1
Type of damage (v3)	0.06	Global damage (w31)	1
		Local damage (w32)	0.5
Type of roofing system (v4)	0.11	Madras terrace style roofing (w41)	1
		Steel truss with roof covering (w42)	0.7
		RC slab (w43)	0.4
Type of structure (v5)	0.26	Masonry (w51)	1
		Reinforced concrete structure (w52)	0.5
Year of construction (v6)	0.33	Before 1900 (w61)	1
		1900–2000 (w62)	0.7
		After 2000 (w63)	0.4

2.4 Damage grade calculation

The mean damage grade is the interpretation of the level of damage sustained by the building in case of a seismic event. The formulation for mean damage grade (μ_D) is expressed as a function of the intensity of earthquake in the macroseismic scale and vulnerability index. For masonry structures, the formulation for mean damage grade as expressed by Giovinazzi and Lagomarsino (2004) is presented in the following equation:

$$\mu_D = 2.5 \times \left(1 + \tanh\left(\frac{I + 6.25V_i - 13.10}{Q}\right)\right) \tag{8}$$

where μ_D is the mean damage grade, I is the macroseismic intensity, V_i is the vulnerability index ($0 \le V_i \le 1$) and Q is the ductility index. The value of mean damage grade varies between 0 and 5 and the damage level is classified based on EMS-98. The conversion of earthquake intensity from the macroseismic intensity to the MSK scale intensity is according to the following equation (Vicente et al., 2011):

$$I_{MSK} = 0.734 + 0.814 \times I_{MCS} \tag{9}$$

The transformation of V_i to the vulnerability index calculated by macroelemental method according to Lagomarsino and Podestà (2004) is expressed in the following equation:

$$V_i = 0.67 + 0.55 \times i_v \tag{10}$$

For reinforced concrete structures, the formulation for mean damage grade as given by Ferreira et al. (2017) is expressed as follows:

$$\mu_D = 2.839 \times \left(1 + \tanh\left(\frac{I + 10.79V_i - 11.60}{Q}\right)\right) \tag{11}$$

where μD is the mean damage grade, I is the macroseismic intensity, Vi is the vulnerability index ($0 \le V_i \le 1$) and Q is the ductility index. Here, V_i can be transformed to the vulnerability index calculated by the macroelemental method according to the method proposed by Ferreira et al. (2017) as follows:

$$V_i = -0.02 + 1.04 \times i_v \tag{12}$$

The mean damage grade formulations from the macroseismic method are derived based on the vulnerability curves drawn on previous European earthquake data. Therefore, these data are compared with grades of damageability obtained from the RVS procedure of the Arya method (Arya, 2011).

2.5 Damage probability matrices

The damage probability matrices are constructed based on the damage index and the binomial probability density function. The damage index is calculated based on the existing level of damage in the structure. The damage score (d_k) with a value between 0 (negligible damage) and 5 (very heavy damage, total near collapse of macroelement) according to Table 5 is attributed to each mechanism. The damage grade is calculated using the following equation (Lagomarsino et al., 2004):

$$i_d = \frac{1}{5} \times \frac{\sum_{k=1}^{28} \rho_k \times d_k}{\sum_{k=1}^{28} \rho_k} \tag{13}$$

TABLE 5 Damage score (d_k) values De Matteis et al. (2016).

Damage score	Definition
0	No damage
1	Negligible to slight damage (no structural damage, slight non-structural damage)
2	Slight structural damage and moderate non-structural damage; many cracks with falling of fairly large pieces of plaster
3	Slight structural damage and moderate non-structural damage; many cracks with falling of fairly large pieces of plaster
4	Heavy structural damage and very heavy non-structural damage,with development of first-mode mechanisms
5	Very heavy damage, with total or near total collapse of the macro-element

TABLE 6 Correlation between damage level (D_k) and damage index (i_d) Lagomarsino and Podestà (2004).

Damage level	Damage index	Description
0	id ≤ 0.05	No damage (slight damage in 1 or 2 mechanisms)
1	0.05 < id ≤ 0.25	Negligible—Slight (slight damage in some mechanisms)
2	0.25 < id ≤ 0.4	Moderate (slight damage in many and medium damage in 1 or 2 mechanisms)
3	0.4 < id ≤ 0.6	Substantial—heavy (medium damage in many and severe damage in some mechanisms)
4	0.6 < id ≤ 0.8	Very heavy (severe damage in many mechanisms and collapse of some elements)
5	id > 0.8	Destruction (more than two thirds of the elements are severely damaged)

where ρ_k is the weight of the mechanism, and d_k is the damage score assigned to each mechanism. The damage level (D) of the building is assumed based on the value of the damage index obtained according to Table 6. The binomial probability density function (BPDF) was used to calculate the probability of the occurrence of a damage having a level k and defined using the following equation (De Matteis et al., 2016):

$$p_k = \frac{5!}{k!\,(5-k)!}\left(\frac{\mu_d}{5}\right)^k\left(1-\frac{\mu_d}{5}\right)^{5-k} \tag{14}$$

where μ_d is the mean damage level calculated for all the buildings based on the value of damage level (D_k) and calculated using the following equation:

$$\mu_d = \frac{\sum_{i=1}^{n} D_{k,i}}{n} \tag{15}$$

3 Data collection and analysis

3.1 Data collection

Historical churches in and around the twin cities of Bhubaneswar and Cuttack cities in Odisha, India, were visually inspected to collect necessary data for the evaluation of the seismic vulnerability index (Figure 2). The classification of the churches based on the type of structure, year of construction, type of roofing system, and the presence of macroelements is displayed in Figure 3.

3.2 Seismic vulnerability assessment

Among the surveyed churches, seismic vulnerability analysis was performed on four buildings, including two masonry and two reinforced concrete buildings (Figure 4). The analysis involves the identification of macroelements in each building, assigning the values of v_{ki} and $v_{k\rho}$, calculation of the weights of the possible damage mechanisms by AHP followed by the calculation of seismic vulnerability index and estimation of the damage grade. Possible representations of collapse mechanisms in the analyzed churches are displayed in Figure 5.

For example, if the facade overturning (mechanism k = 1) is considered for the Church of Epiphany (Cuttack), it has numerous buttresses ($v_{k\rho}$ = 2) and lunettes of small sizes (v_{ki} = 1). The building is a primary seismic element, kinematic is out of plane, failure is global, madras terrace styling roof, masonry structure, and was constructed before 1900. Therefore, Eq. 7 provides a weight (ρ_k) of 0.99. The damage score (d_k) of 1 was assigned to the mechanism because of the slight existing damage. The current state of the analyzed church buildings and their seismic vulnerability indices and damage levels are explained in subsequent structures.

3.2.1 Church of epiphany, Cuttack

Church of Epiphany (Figure 2F) constructed in the year 1826, is one of the oldest churches in Cuttack city. This historical building is a masonry structure with timber truss roof and a built-in madras terrace roofing style. The structure replicates ancient

FIGURE 2
(A) Pipili Baptist Church, Pipili **(B)** Ashraya Pur, Jamkouli **(C)** St. John Church, Jatni **(D)** St. Vincent Pro's Cathedral, Bhubaneswar **(E)** Bahilipada Church, Barakuda **(F)** Church of Epiphany, Cuttack **(G)** Our Lady of Most Holy Rosary Cathedral, Cuttack **(H)** Mount House Church of God, Cuttack **(I)** Sacred Heart Church, Jatni **(J)** Oriya Baptist Church, Jatni.

church architecture with a pitched roof, a bell tower erected at the east end of the church, and buttresses all around the structure. The narthex at the front end is a reinforced concrete structure constructed in subsequent years. Based on the possible damage mechanisms, the vulnerability index (vki) was obtained as 0.716. The high value of the seismic vulnerability index could be attributed to the presence of cracks and deterioration in roof, triumphal arch, and other elements of the building. The damage index (id) was obtained as 0.285, and therefore, the damage level (Dk) of the whole structure was 2. According to the Arya method (Arya, 2011), this church building can be classified [23] to be B+, that is, unreinforced brick masonry in lime mortar.

3.2.2 Sacred Heart Church, Jatni

Sacred Heart Church (Figure 2I) is one of the old churches in Jatni, Odisha. The church is a masonry structure with madras terrace style roofing and is more than 50 years old. A cruciform structure can be observed in the plan view. The roof is strengthened by the addition of steel beams in the transverse direction. Buttresses are present on the exterior of the structure. Arch structures can be observed on the sides of the building. Based on the possible damage mechanisms, the vulnerability index (v_{ki}) was obtained to be 0.528. Even though the building is old, the addition of transverse steel beams in the roof reduces the vulnerability level. The damage index (i_d) is obtained as 0.175, and the damage level (D_k) of the whole structure is 1. According to the Arya method (Arya, 2011), the building can be classified as C, that is, unreinforced masonry walls with roof and horizontal bracing.

3.2.3 Bahilipada Church, Barakuda

Bahilipada Church (Figure 2E) is a 100-year-old cruciform-shaped church in Barakuda, Odisha, and is similar to many cathedrals and historical churches. The church has undergone renovations, and a new reinforced concrete building was constructed to address vulnerability concerns. Based on the possible damage mechanisms, the vulnerability index (v_{ki}) was 0.35. The damage index (i_d) was obtained to be 0.05, and the damage level (D_k) of the whole structure is 0. According to the Arya method (Arya, 2011), the building can be classified as C+, that is, the MR-RCF of ordinary design without earthquake or wind resistant design with unreinforced masonry infill.

3.2.4 St. Vincent's Pro Cathedral, Bhubaneswar

St. Vincent's Pro Cathedral (Figure 2D) is one of the oldest churches in Bhubaneswar, Odisha, The cathedral was opened to

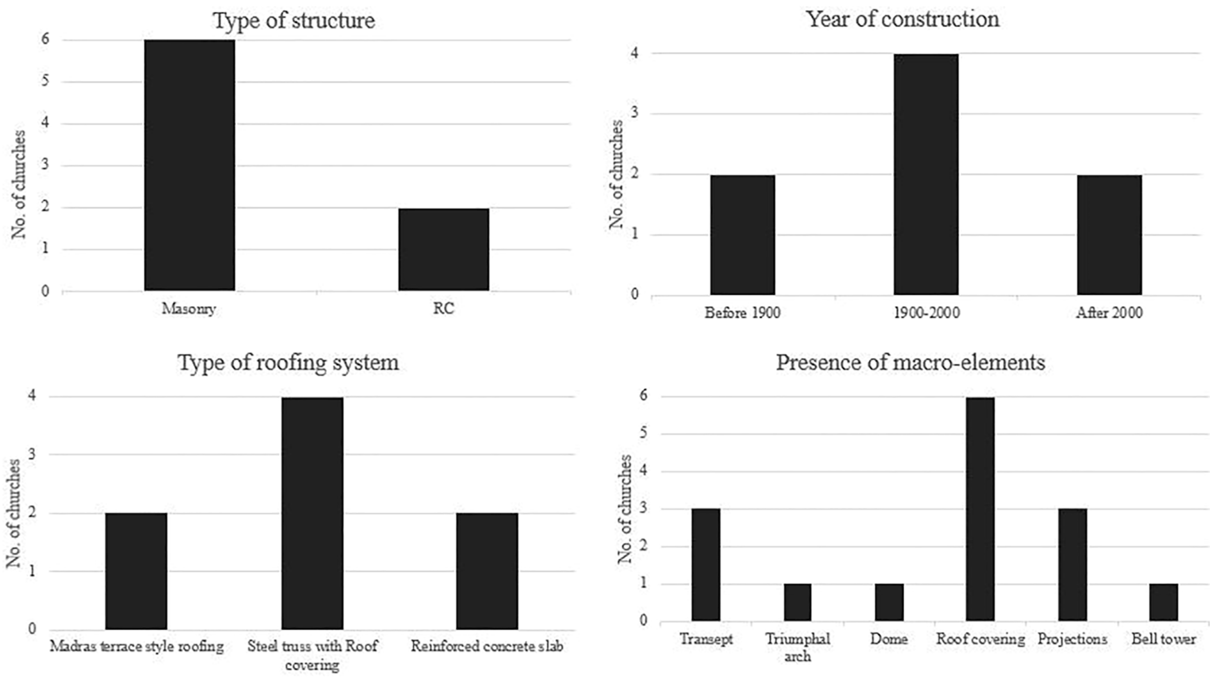

FIGURE 3
Analysis of surveyed church data.

FIGURE 4
(A) Church of Epiphany, Cuttack **(B)** Sacred Heart Church, Jatni **(C)** Bahilipada church, Barakuda **(D)** St. Vincent Pro's Cathedral, Bhubaneswar.

FIGURE 5
Possible collapse mechanisms in the analyzed churches.

FIGURE 6
Mount House Church of God, Cuttack.

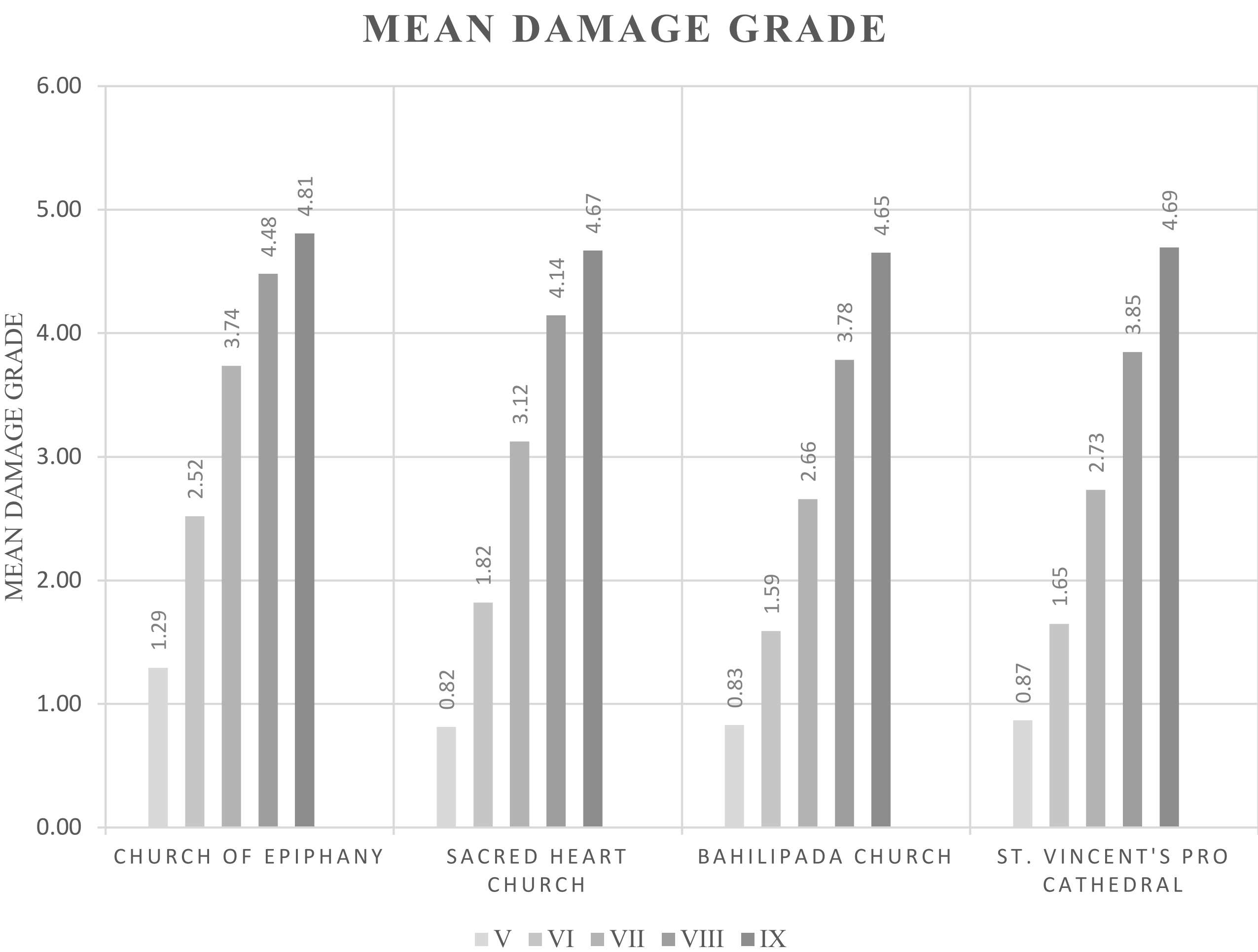

FIGURE 7
Comparison of mean damage grade values for various churches.

public in the year 1968. The church is a reinforced concrete structure with a non-structural dome. This church is a pro-cathedral with a cruciform shape. Based on the possible damage mechanisms, the vulnerability index (v_{ki}) was 0.357. The damage index (i_d) is obtained as 0.123, and the damage level (D_k) of the whole structure is 1. According to the Arya method (Arya, 2011), this building can be classified as C+.

3.2.5 Mount House Church of God, Cuttack

Mount House Church of God (Figure 2H) is a 120-year-old church situated in Cuttack, Odisha. The masonry building is currently being demolished, and a new RC building is being constructed as displayed in Figure 6. The old masonry structure has a madras terrace roof in the nave and side aisle parts of the building, and it is strengthened by the addition of longitudinal steel girders along with the timber beams. The walls and entry arches were made of brick masonry. Reconstruction of the new building was undertaken because of the high seismic vulnerability of the existing masonry structure. The new building was a reinforced concrete structure, which was constructed to look like the original church building while at the same time providing seismic resistance that was not present in the old masonry structure. Cracks were observed on the walls and some roof elements of the half-demolished structure. The structure is a reinforced concrete structure with confined masonry. The confined masonry type of construction is known to exhibit superior earthquake resistant properties compared with conventional RC structures. Therefore, the method can be adopted to overcome the seismic vulnerability problems.

4 Results and discussion

A field study was conducted on old and historic church buildings in and around the Bhubaneswar–Cuttack twin

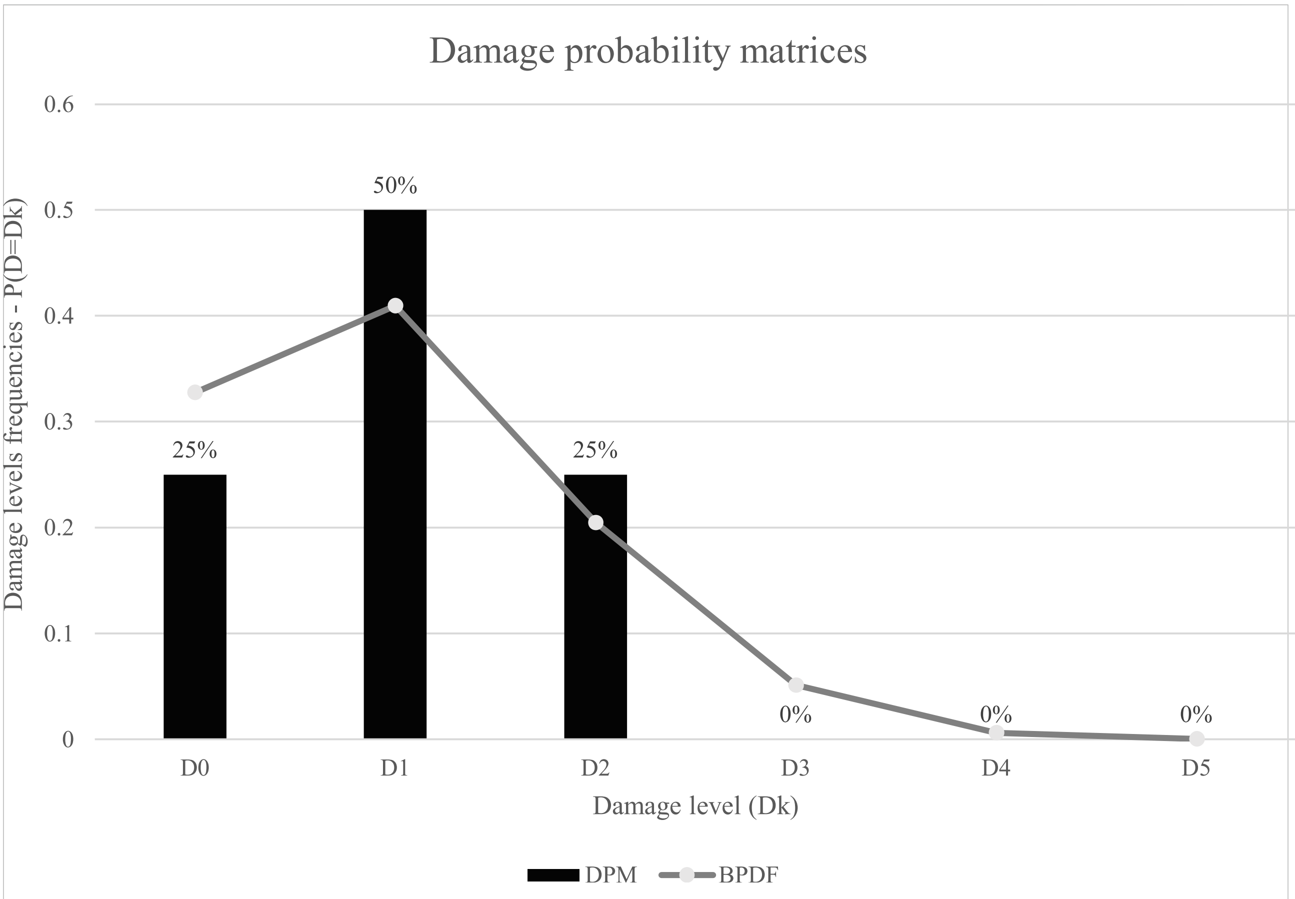

FIGURE 8
DPMs for analyzed churches.

cities. Of the eight churches on which the field study was conducted, four churches (two masonry buildings and two RC buildings) were selected for seismic vulnerability assessment. The macroelemental method with all the possible damage mechanisms proposed by Lagomarsino et al. (2004) was used for calculating the vulnerability index. The weights of parameters were calculated using the analytical hierarchy process. The criteria and parameters required for AHP were used as described by Uva et al. (2019), and new criteria/parameters were added based on the structural typology of the surveyed churches. The mean damage grade was calculated to estimate the damage at various earthquake intensities according to the equation given by Giovinazzi and Lagomarsino (2004) for masonry buildings and (Ferreira et al., 2017) for RC buildings. The damage was classified based on the obtained value of the mean damage grade according to the EMS-98 scale (Grünthal, 1998) a and compared with the grade of damageability obtained using the RVS method for Indian conditions (Arya, 2011). Damage probability matrices were constructed to determine the probabilistic future damage.

4.1 Mean damage grades

The mean damage grades according to the macroseismic method for the four churches at earthquakes of various intensities are displayed in Figure 7. The damage level of all buildings varied from negligible for an intensity of V to very heavy damage for an intensity of IX. However, higher values of damage grade were observed for the Church of Epiphany, Cuttack, than those for other churches because of its higher vulnerability index. The damage grades were lower than with the RVS method for Indian conditions. For an intensity of VII on the MSK scale, the Church of Epiphany has a damage grade of 3.73, which represents a possibility of heavy to very heavy damage according to EMS-98. A moderate grade of damageability was estimated according to the RVS method for the same intensity of earthquake. The damage grade of Sacred Heart Church for this intensity was 3.12, which represents a possibility of substantial damage according to EMS-98 and slight damage according to RVS because both buildings were old masonry structures, the anti-seismic elements (buttresses, tie rods) were not effective. The other two churches are likely to sustain moderate damage from an earthquake of intensity VII because they are newly constructed RC structures. Because the cities are situated in Zone III, which is a moderate seismic risk zone, an earthquake of intensity of VIII or IX on the MSK scale is not likely to occur in these regions. Therefore, the higher values of mean damage grade should not be considered in the seismic design of these structures.

4.2 Damage probability matrices

The damage probability matrices based on the current damage state are displayed in Figure 8. DPMs revealed that the St. Vincent Pro's Cathedral and Sacred Heart Church have 41% probability of D1 level (negligible-slight) damage, while the Church of Epiphany had 20.50% probability of D2 level (moderate) damage in case of an earthquake of V–VI (MSK) intensity.

5 Conclusion

The seismic performance of constructed facilities was evaluated to understand the seismic behavior of existing facilities. The research is a practice-oriented paper on using macromodelling techniques for fast seismic assessment of churches and prioritizes those churches that need immediate intervention and informing the stakeholders of the building about possible collapse risks. This is particularly applicable to the rehabilitation of existing masonry structures, which are not earthquake resistant. The macro element approach of seismic vulnerability assessment can be applied for evaluation of the seismic vulnerability and, following it, identified structures can be suggested for further retrofit solutions. Based on the analysis, the following conclusions were drawn for the existing churches located in the Odisha region.

The Church of Epiphany, Cuttack, with a seismic vulnerability index of 0.716, is the most vulnerable to earthquakes among the surveyed churches, whereas the least vulnerable church was Bahilipada Church, Barakuda, with a vulnerability index of 0.35.

The damage grades obtained from the mean damage grade formulations were higher than those of damageability obtained through the RVS method for Indian conditions.

The mean damage grade values indicate that the Church of Epiphany and Sacred Heart Church can be substantially damaged in case of an earthquake of VII (MSK) intensity, whereas the other two churches can be moderately damaged. Furthermore, the RVS method estimates moderate damage for the Church of Epiphany and slight to negligible damage to other churches for the same earthquake intensity.

DPMs revealed that the St. Vincent Pro's Cathedral and Sacred Heart Church have 41% probability of D1 level (negligible-slight) damage and the Church of Epiphany has 20% probability of D2 level (moderate) damage in the event of an earthquake of V–VI (MSK) intensity.

Considering the overall analysis, the 150-year-old Church of Epiphany required the utmost attention because its seismic vulnerability was higher than other buildings. Immediate retrofitting techniques, such as surface treatment, epoxy injection, and external reinforcement, should be used to preserve the heritage structure from heavy damage. The other three structures were renovated. Therefore, damage probability matrices suggest seismic vulnerability and the probability of damage is low.

As highlighted in the paper, Mount House Church of God, Cuttack, was rebuilt using modern reinforcement concrete solutions, which resemble its old architectural style. In this way, the original form of the building is retained while making it seismically resistant at the same time, acting as a double-edged sword, thus serving both purposes. The solution highlighted in this case study can be used for other applications where seismic upgrade of existing masonry buildings is desired or possible, replacing them with reinforced concrete but preserving the old architectural style. Thus the seismic upgrade solution can be transferred to other structures.

In the future, seismic vulnerability curves should be constructed for the estimation of probabilistic future damage and the development of new structural health monitoring techniques, considering the local empirical construction methodologies, material characterization, different ceiling systems, and construction techniques of Indian vernacular architecture. This will aid in carrying out detailed structural analysis of churches using micromodeling techniques and validation of modal parameters by performing field ambient vibration tests. Detailed structural analysis of common typologies of churches will also be a step towards validation of failure mechanisms. Furthermore, additional post-earthquake seismic vulnerability assessments should be conducted in the Indian region for realistic assessments in cases where damage due to an earthquake can be determined.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

MM and RP were involved in all steps of the manuscript preparation, site-visits, revisions, reading, corrections, approval, and submission. GR was involved in the final reading of the manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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