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Application of Macroseismic Method to Analyze Construction Materials and Seismic Enhancement Dynamics in the Reconstruction of Nepalese Multi-tiered Temples

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Abstract
The 2015 Gorkha earthquake caused heavy damage to the historically and archeologically important multi-tiered temples in Kathmandu Valley. The high seismic vulnerability of the tiered temples built in traditional construction materials and technologies have become clearly evident through the damage assessments, prompting the need for seismic strengthening measures in their reconstruction. The post-earthquake restoration and reconstruction projects of the damaged monuments have been mostly completed, incorporating seismic strengthening measures. Very few research can be found related to the quantification-based studies regarding the vulnerability of the multi-tiered temples and variation in material, cost and seismic performance due to the incorporation of such seismic retrofitting measures, which this research study has addressed. The Macroseismic method of vulnerability assessment has been implemented in this research, which helps to measure the vulnerability of a building or group of buildings in terms of parameters such as, Vulnerability Index and Ductility Index, taking account of the building typology and its constructive features when seismic hazard is provided in terms of Macroseismic intensity. The method provides a vulnerability model which enables to forecast the probable damage distribution for a given intensity of earthquake. This study consists of the case history analysis of the two three-tiered temples of Kathmandu Valley, namely, Harishankara Temple of Patan and Bamsa Gopal Temple of Kathmandu, constructed in traditional material and technology. The findings of this research indicate that the seismic vulnerability of the tiered temples is significantly reduced due to the incorporation of seismic strengthening measures even with very less increment in the cost. The vulnerability model is intended to be helpful to the policy makers in the planning of the future projects involving restoration and reconstruction of tiered temples built in traditional materials and technology.

Keywords
Multi-tiered Temple, Traditional construction, Seismic strengthening, Macroseismic vulnerability assessment, Cost analysis

1. Introduction

The multi-tiered temples of Kathmandu Valley embodies a unique cultural value and historical legacy of temple architecture and traditional construction technology, thus enlisted in the UNESCO World Heritage Site due its Outstanding Universal Value. Most of the multi-tiered temples in Kathmandu Valley are more than three centuries old built in traditional construction materials and technology. Nepal being in seismically vulnerable zone, have prior documented major earthquake events causing damage to human lives as well as the multi-tiered temples, an integral part of Nepalese culture and lifestyle, which were consequently restored and renovated overtime [1, 2, 3]. The recent 2015 Gorkha earthquake of 7.8 Magnitude rendered heavy damage to many numerous heritage structures including tiered temples causing complete collapse of structure to serious damages [3, 4]. With the initiation of Nepal Reconstruction Authority (NRA) under the supervision of Department of Archeology (DOA), restoration and reconstruction projects of heritage structures have been performed. The aforementioned facts indicate that our precious heritages including the multi-tiered temples are undoubtedly seismically vulnerable. Thus, the seismic enhancement measures for strengthening of such structures can play a pertinent role in the heritage conservation and preservation, however, with minimal intervention to their original fabric maintaining it's authenticity to most possible extent [4]. As most of the restoration and reconstruction projects are completed, various seismic enhancement approaches have been adopted in the reconstruction of various tiered temples. The restoration and conservation projects of heritage structures are ever more challenging due to the necessity of stringent adherence to international and national conservation guidelines in order to maintain the authenticity of their heritage values. On the other hand, such projects are always challenged with unexpected issues during execution and considerably resource extensive in terms of cost, labor and materials [5, 6].

The quantification-based studies regarding the variation in material, cost and seismic performance due to the incorporation of seismic enhancement measures in the heritage structures is very limited, this research is oriented towards studying this gap of knowledge. This study is based on the Macroseismic Vulnerability approach that helps to understand the dynamics between the adoption of seismic enhancement measure and the subsequent variation in the construction material and cost in the reconstruction projects. This study considers only the case of three to four storied multi-tiered temples of Kathmandu Valley built in traditional construction materials and technology, during 18th century. The research intends to provide insights upon the prediction of expected damage levels for different intensity of earthquakes in future that can be helpful to the policy makers in preparing necessary planning measures for similar reconstruction and renovation projects in the near future.

2. Literature Review

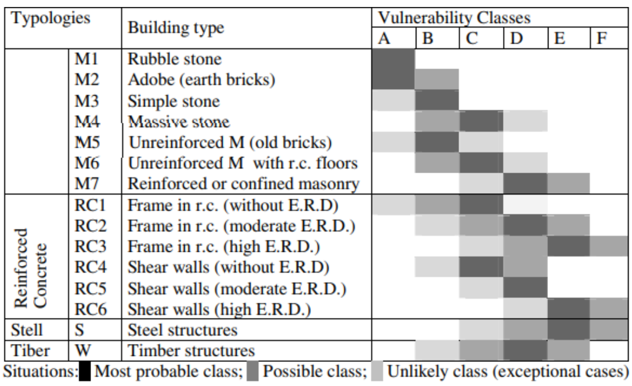
2.1 Seismic Vulnerability Assessment

The seismic vulnerability of a structure is related to the measure of its weakness when exposed to the earthquake of a given intensity, thus, the seismic vulnerability assessment allows the evaluation of expected damage of future earthquakes of given intensity [7].

2.1.1 EMS Scale definitions and Damage Probability Matrix

The EMS-98 Macroseismic scale defines the measurement of earthquake shaking in terms of 12 degrees of intensities in increasing order, based on the observed damage in building structures [8, 9]. Whereas, the level of damage suffered by the structures are classified into 5 grades, identified as D_k(k = 0/5): D_1-slight, D_2-moderate, D_3-heavy, D_4-very heavy, D_5-destruction, plus the absence of damage D_0-no damage [9]. Furthermore, based on the similar seismic behavior shown by the building typologies, they are grouped into six vulnerability classes, from most to least vulnerable as given in the figure 1. The vulnerability table provides the correlation of the seismic behavior of building typologies with vulnerability classes. Various factors such as, workmanship, condition of preservation, quality, ductility, regularity, position, strengthening, earthquake resistant design, consistency of code and level of importance are taken into consideration. The classification enables uniform data interpretation and results by maintaining consistency in representing the seismically exposed building structures and the damage observed [8].

The EMS-98 damage probability matrix describes the damage pattern of each vulnerability class for each level of Macroseismic intensity of earthquake linguistically using the quantitative terms “Few”, “Many”, “Most”, which is rather vague. However, damage probability matrices from EMS-98 is incomplete, vague and qualitatively descriptive, that categorizes different building typologies only into most probable vulnerability classes along with most probable to less probable range of seismic behaviors, thus, rendering it difficult for application in vulnerability assessment purpose [10].



Typologies		Building type	Vulnerability Classes					
			A	B	C	D	E	F
	M1	Rubble stone						
	M2	Adobe (earth bricks)						
	M3	Simple stone						
	M4	Massive stone						
	M5	Unreinforced M (old bricks)						
	M6	Unreinforced M with r.c. floors						
	M7	Reinforced or confined masonry						
Reinforced Concrete	RC1	Frame in r.c. (without E.R.D)						
	RC2	Frame in r.c. (moderate E.R.D.)						
	RC3	Frame in r.c. (high E.R.D.)						
	RC4	Shear walls (without E.R.D)						
	RC5	Shear walls (moderate E.R.D.)						
	RC6	Shear walls (high E.R.D.)						
Stell	S	Steel structures						
Tiber	W	Timber structures						

Situations: Most probable class; Possible class; Unlikely class (exceptional cases)

Figure 1: EMS-98 Vulnerability Table

2.1.2 Macro-Seismic Method of Vulnerability Assessment

The Macroseismic method is an empirical approach for the vulnerability assessment of a group of buildings or even a single building, incorporating EMS scale definitions [8, 11]. The vulnerability assessment is carried out using qualitative parameters, measured in terms of Vulnerability Index *(V)* and Ductility Index *(Q)*, when the seismic hazard is provided in terms of Macroseismic intensity *(I)*, [8, 11]. This method is based on the Damage Probability Matrices assigned to each of the vulnerability classes according to various building typologies. The structural and constructive characteristic features of a building typology that determines the seismic behavior, are considered [8].The vulnerability assessment is expressed in a closed analytical function,as expressed in equation 1, that correlates the seismic input and the damage expected, as a function of the assessed vulnerability [8].

$$\mu_D = 2.5\left[1+\tanh\left(\frac{I+6.25V-13.1}{Q}\right)\right] \tag{1}$$

where, $\mu_D(0<\mu_D<5)$, is Mean Damage value. The correlation function thus derived can be represented in the graphical format, named as the vulnerability curves applicable in the evaluation and analysis of the seismic vulnerability of various building typologies. The method is considered reliable as it has been verified on the basis of data observed after different earthquakes in different countries. The method provides a vulnerability model which enables to forecast the probable damage distribution for a given intensity of earthquake[8]. Furthermore, the classical probability theory and the fuzzy-set theory are applied in this method to address the incompleteness and vagueness in the description of EMS-98 scale [8, 11].

The incompleteness of damage probability matrices from EMS-98 scale, is addressed in this method using the classical probability theory, introducing a proper discrete probability distribution of damage grade. The Beta distribution is applied as it helps to better define the damage grade around the mean value, even when the value of mean damage grade is quite low [8]. Furthermore, this method also solves the vagueness of EMS-98 by translating the linguistic description of the EMS scale definitions, according to the fuzzy set theory assigning membership function to the vulnerability classes of each building typology. Thus, each building typology is assigned a representative value of vulnerability index (V) as provided in the figure 2. Further the typological vulnerability index table consists of probable and less probable range of vulnerability Index, referred to respectively as V^-/V^+ and V^{--}/V^{++}, associated with each vulnerability class [10].

The Vulnerability Index (V) of a particular building typology signifies the particular vulnerability class it belongs to. The value of (V) is derived from scoring approach that quantifies the behavior of the building, which basically represents a measure of the seismic vulnerability of the building, as defined by equation 2 [11]

$$V = V_I + \Delta V_R + \Delta V_m \tag{2}$$

where, V_I is a Typological Vulnerability Index ΔV_R is a Regional Vulnerability Index ΔV_m is a Seismic Behavior Modifiers. However, the final vulnerability index has to be in between the highest and lowest probable range of the typological vulnerability index for that building typology [8, 10].

Typologies		Building type	V^{--}	V^{-}	V_I	V^{+}	V^{++}
Masonry	M1	Rubble stone	0.62	0.81	0.873	0.98	1.02
	M2	Adobe (earth bricks)	0.62	0.687	0.84	0.98	1.02
	M3	Simple stone	0.46	0.65	0.74	0.83	1.02
	M4	Massive stone	0.3	0.49	0.616	0.793	0.86
	M5	U Masonry (old bricks)	0.46	0.65	0.74	0.83	1.02
	M6	U Masonry—r.c. floors	0.3	0.49	0.616	0.79	0.86
	M7	Reinforced /confined masonry	0.14	0.33	0.451	0.633	0.7
Reinforced Concrete	RC1	Frame in r.c. (without E.R.D)	0.3	0.49	0.644	0.8	1.02
		Frame in r.c. (moderate E.R.D.)	0.14	0.33	0.484	0.64	0.86
		Frame in r.c. (high E.R.D.)	−0.02	0.17	0.324	0.48	0.7
	RC2	Shear walls (without E.R.D)	0.3	0.367	0.544	0.67	0.86
		Shear walls (moderate E.R.D.)	0.14	0.21	0.384	0.51	0.7
		Shear walls (high E.R.D.)	−0.02	0.047	0.224	0.35	0.54

Figure 2: Vulnerability Index Values for Building Typologies [10]

2.2 Quantity Survey and Cost Estimation

Estimation is a technique of calculating various quantities and the expected cost to be incurred on a particular work or project, that helps to determine the feasibility of a project. It plays an essential role in the field of construction management by helping in the control and monitoring of a construction project during the execution phase. The estimation of a construction project requires Drawings, Specifications and Rates involving mainly two stages viz., Detail measurement and calculation of Quantities and preparing Abstract of Estimated Cost in a tabular format. The unit rate of each unit of work needs to be calculated considering standard norms, wages of labors, material rates, cost of equipment, profits and overheads and others. The estimation of heritage reconstruction projects are unique from the modern constructions regarding the materials and techniques resulting in considerable difference in the material rates and labor wages, thus Department of Archeology (DOA) have been referred in this research while District rates of Kathmandu and Lalitpur along with quotations from vendors were also referred for rate analysis of certain items. The necessary drawings were obtained from DOA and published documents.

3. Research Methodology

The research includes the study of the tiered temples, more than three centuries old from Malla Dynasty eras, embodying unique architecture built in traditional materials and technology. In the context of devastating 2015 Gorkha earthquake, the study is oriented towards the completed reconstruction projects of the three to four storied tiered temples of Kathmandu Valley which were completely collapsed during the event of earthquake to address the research problems. In the Magnitude 7.8 Gorkha earthquake more than 2,900 monuments were affected, including 133 that completely collapsed from the plinth level, 95 severely damaged and 513 partially damaged [3]. However, case history analysis of only two tiered temples have been carried out in this research, as a representative cases for similar structures, also allowing in-depth study necessary for identifying parameters for the analysis and deriving conclusions efficiently and effectively . The first case is the Harishankara Temple of Patan Durbar Square and second being Bamsa Gopal Temple of Kathmandu Durbar Square. Both of the temples are three tiered that were completely collapsed during the earthquake and reconstructed in its earlier form and shape with the application of seismic strengthening measures. The detail study of the cases was carried out from the data collected from reports, published books and journal, direct observation, on-site measurements. Informal interviews of the experts and technicians directly involved in the reconstruction projects of the selected cases were performed to obtain necessary information related to the cases as well as to validate the secondary data. Informal interviews with the technical engineers from Department of Archaeology (DOA) and Kathmandu Valley Preservation Trust (KVPT) as well as other conservation experts were also carried out.

The research is based on an empirical approach adopting the Macroseismic Method of vulnerability assessment developed by [8, 11], based on the EMS-98 scale definitions, to address the first objective of the research. Unlike other methods, this method helps to quantify the seismic vulnerability of single or group of building structures of different typologies enabling further evaluation and analysis through observation [12, 13]. Furthermore, the seismic vulnerability assessment was carried out for the two cases of tiered temples before and after the seismic strengthening during their reconstruction that completely collapsed during the 2015 Gorkha earthquake. Foremostly, the building typology of the temples was identified based on their structural and constructive features, then classified into corresponding vulnerability class. By referring to vulnerability Index table in figure 2, corresponding value of Typological Vulnerability Index (V_I) was obtained, for both the pre-earthquake as well as post-earthquake scenario. The value for the regional modifier factor (ΔV_R) , is adopted as 0.08. Similarly, the value of Behavior modifiers is derived by scoring of the parameters for Seismic Behavior Modifiers (ΔV_m) through expert's judgment. The Vulnerability Index V for both the cases is calculated using equation 2. The seismic vulnerability curve was derived using the equation 1, as graphically represented in figure 4 showing vulnerability curve, illustrating the mean damage grade level for different Macroseismic intensity level(I) for before and after earthquake scenarios.

Whereas, for the second objective, the detail drawings and cost estimation collected related to the two cases were calculated and cost summary for the various materials of both the temples were extracted for two scenarios, first being the before earthquake phase and later being post earthquake reconstruction phase. This provided the information regarding the type of materials used in the original construction methods and technology, furthermore, regarding how new materials and to what extent the seismic enhancement mesaures were adopted in the post earthquake scenarios. Thus, the variation in the cost of materials for the two scenarios were derived for both temple cases for further analysis and discussion.

The results thus obtained from above analyses were discussed and interpreted, then the results and conclusions were drawn. The process is further illustrated in methodology flowchart shown in figure 3.

4. Case History Analysis

4.1 Case I: Harishankara Temple, Patan Durbar Square

Built in 1706, Harishankara temple is located in Patan Durbar Square in west side opposite to the *Taleju* temple of the palace complex. It is three – tiered, raised on three stepped plinth platforms, consisting of a squared enclosed sanctum surrounded with an outer ambulatory in ground floor and first floor

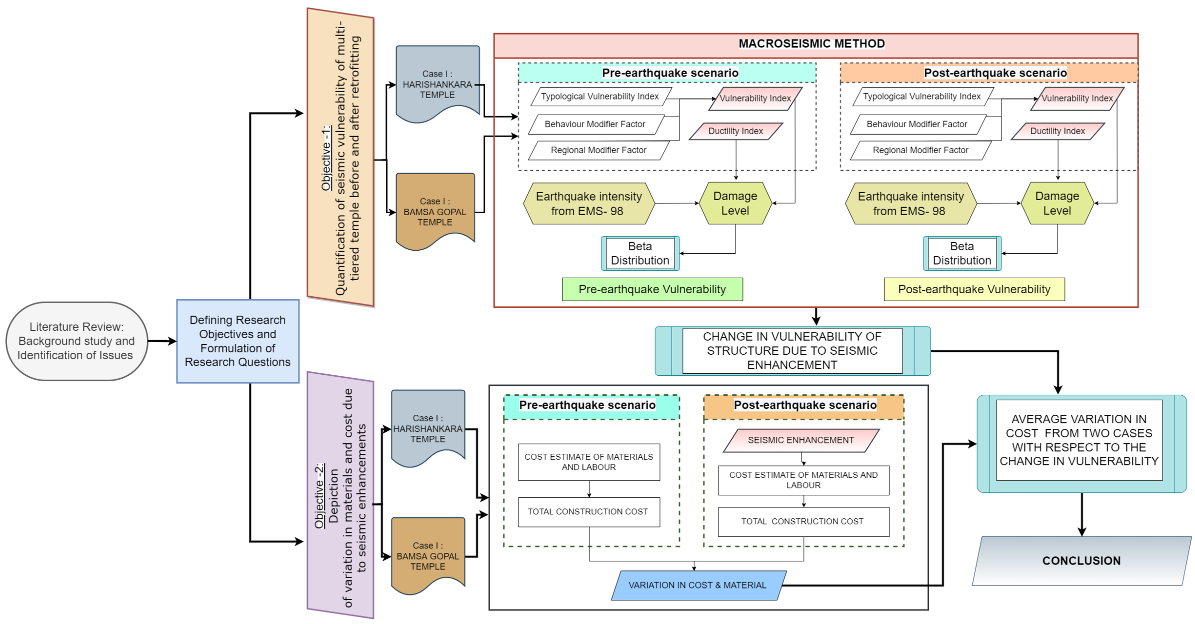


Figure 3: Methodological framework for vulnerability characterization

consisting of outer and inner wall with a passage in between, with the inner sanctum wall continuing from ground floor and outer wall rests on the ambulatory column and beam structure. Then, each tier has sloped roofing supported by wooden struts with pinnacle at the top. The major construction materials are brick, timber, terracotta tiles, stones and metals. The brick masonry wall in mud mortar is the main load bearing structure along with the framed structure of wooden column, beams and joists. During the event of 2015 Gorkha earthquake, Harishankara temple completely collapsed, due to major two causes, first being the failure in the connection of the columns and base stones of the outer ambulatory in ground floor and the second being discontinuous ring of stone in the inner sanctum causing the independent movement under the lateral seismic forces. The reconstruction project was completed (2015 – 2019) under the technical support of KVPT, restoring the temple to its former configuration using traditional methods and techniques, yet incorporating seismic enhancements to enhance the seismic performance with least compromise on the authentic fabric and structure of the temple. Thus, the reconstruction project of Harishankara temple implicating the cost variation and other uncertainties. Major measures of seismic strengthening included use of stainless-steel angle and bolt to tie cross beams, extended length of cross beams with additional cross beams at core, Glass Fiber Reinforced Polymer (GFRP) Bars, increase in size of wall plates and others.

Evaluation of Vulnerability Index: In the case I, for pre-earthquake scenario, from the detail study and analysis of its constructive features, it was classified as building typology (M5) and identified as Vulnerability Class B, based on figure1. From the figure 2, the corresponding V_I was obtained as 0.74. Consequently, the sum of the scores of ΔV_m was derived as 0.16, in reference to the scoring carried out as per figure 3. The value of ΔV_R was considered as 0.08 as provisioned in the Macroseismic method. Similarly, the post- earthquake scenario details was derived as shown in table 1, which indicates the Vulnerability Index (V) derived using equation 2, for the post-earthquake scenario reduced more than by half with respect to pre-earthquake scenario. The value of mean damage level for different Macroseismic intensities level were calculated for both scenarios, using the equation 1 as shown in table 2. The table 2 indicates, the average reduction in the value of damage level, due to the seismic enhancement, to be **69.82%**.

Table 1: Case History Analysis of Harishankara Temple

	Pre-Earthquake Scenario	**Post-Earthquake Scenario**
Building Typology	(M5) unreinforced old brick masonry category	(M7) confined masonry category
Vulnerability Class	Class B	Class D
Typological Vulnerability Index (V_I)	0.74	0.451
Behavior Modifier(ΔV_m)	0.16	-0.12
Regional Modifier (ΔV_R)	0.08	0.08
Vulnerability Index (V)	0.98	0.411
Cost Summary (in NRs.)	80,067,801.35	85,528,421.64

Cost Analysis The incremental variation in the cost of the Harishankara temple due to the additional materials for the seismic strengthening of the temple have been found to be **6.82%**.

4.2 Case II: Bamsa Gopal Temple, Kathmandu Durbar Square

Built in 1705, *Bamsa Gopal* temple is located in Kathmandu Durbar Square in north-west side opposite to the *Degu Taleju* temple of the palace complex. It is three – tiered, raised on five stepped plinth platforms, consisting of an octagonal shaped plan with enclosed sanctum surrounded with an outer ambulatory in ground floor and first floor consisting of outer and inner wall

Table 2: Mean Damage value of Harishankara Temple, for different Macroseismic Intensity Level of earthquake

Macroseismic Intensity Level (*I*)	Pre-Earthquake Mean Damage Level (μ_{D1})	Post-Earthquake Mean Damage Level (μ_{D2})	Difference in Vulnerability (μ_{D1} - μ_{D2})
5	0.761	0.040	94.69
6	1.499	0.095	93.64
7	2.527	0.222	91.23
8	3.546	0.498	85.95
9	4.267	1.045	75.52
10	4.664	1.933	58.56
11	4.853	3.003	38.14
12	4.938	3.910	20.81

with a passage in between, with the inner sanctum wall continuing from ground floor and outer wall rests on the ambulatory column and beam structure. Then, each tier has sloped roofing supported by wooden struts with pinnacle at the top. The major construction materials are brick, timber, terracotta tiles, stones and metals. The brick masonry wall in mud mortar is the main load bearing structure along with the framed structure of wooden column, beams and joists. During

Table 3: Case History Analysis of Bamsa Gopal Temple

	Pre-Earthquake Scenario	Post-Earthquake Scenario
Building Typology	(M5) unreinforced old brick masonry category	(M7) confined masonry category
Vulnerability Class	Class B	Class D
Typological Vulnerability Index (V_I)	0.74	0.451
Behavior Modifier(ΔV_m)	0.16	-0.10
Regional Modifier (ΔV_R)	0.08	0.08
Vulnerability Index (V)	0.98	0.431
Cost Summary (in NRs.)	76,374,941.60	76,743,801.75

the event of 2015 Gorkha earthquake, Bamsa Gopal temple was completely collapsed. The cause of failure is similar mainly due to lack of proper connection of substructure and super structure as well as lack of regular maintenance of the temple. The reconstruction project was completed (2017 – 2019) under the supervision of DOA, complying the Post-Earthquake Conservation Guidelines 2072 and Manual, 2073. The reconstruction of the temple to its former configuration using only traditional methods and techniques, was carried out incorporating seismic enhancements to enhance the seismic performance with least. Thus, the reconstruction project of the temple implicating the cost variation and other uncertainties. Major measures of seismic strengthening included use of additional wooden members in the masonry wall with interconnecting wall ties, additional wall plates and extensive use of wooden chukuls to strengthen the wooden member connections.

Table 4: Mean Damage value of Bamsa Gopal Temple, for different Macroseismic Intensity Level of earthquake

Macroseismic Intensity Level (*I*)	Pre-Earthquake Mean Damage Level (μ_{D1})	Post-Earthquake Mean Damage Level (μ_{D2})	Difference in Vulnerability (μ_{D1} - μ_{D2})
5	0.761	0.045	94.08
6	1.499	0.106	92.93
7	2.527	0.246	90.27
8	3.546	0.549	84.51
9	4.267	1.137	73.35
10	4.664	2.063	55.77
11	4.853	3.131	35.48
12	4.938	4.000	18.99

Evaluation of Vulnerability Index: Similarly as in case I, the Vulnerability Index, for the case II was derived as shown in table 3, that shows significant decrease in the vulnerability index value of the temple structure, more than by half of the initial vulnerability. Similarly, the value of mean damage level for different Macroseismic intensities level were calculated for both pre-earthquake and post earthquake scenarios,as shown in table 4. The table 4 indicates, the average reduction in the value of damage level, due to the seismic enhancement, to be **69.17%**,showing significant decrease in the damage level.

Cost Analysis The incremental variation in the cost of the Bamsa Gopal temple due to the additional materials for the seismic strengthening of the temple have been found to be **0.48%**

5. Results and Discussions

In this research, the Macroseismic method of vulnerability assessment was applied to analyse the average variation in the seismic vulnerability for the two cases of tiered temples of three storied each, built in traditional construction. The seismic vulnerability was found to have reduced significantly due to seismic strengthening measure graphically apparent in the figure 4.

Furthermore, considering the real case scenario damage level observed during the 2015 Gorkha earthquake, both tiered temple in this research, were completely collapsed, that according to the definition of EMS scale, can be classified as Grade 5 and EMS intensity level of VIII. So, while comparing the real case scenario analysis, average reduction in the damage level of the temple was found to be **89%**. This shows the gap in the absolute reduction in the damage level, reflecting the short-coming of this Macroseismic method of seismic vulnerability assessment, as this method fails to incorporate one of the essential parameters that addresses the major cause of failure in most of the tiered temples. Various research and studies reviewed on the construction system and seismic behavior of tiered temples in this research, have emphasized on the cause of failure in the tiered temples built in traditional materials and technology during the 2015 Gorkha earthquake to be the weak connection between the superstructure and substructure. Thus, this method of seismic vulnerability assessment can be modified addressing this missing parameter to improve the analysis and further research in this field.

Regarding the variation in cost for construction of the tiered temples built in traditional material and technology, for before and post 2015 Gorkha earthquake scenarios, the average variation in cost due to the adoption of seismic retrofitting measure have been analyzed and found to be fairly low as **3.6%**.

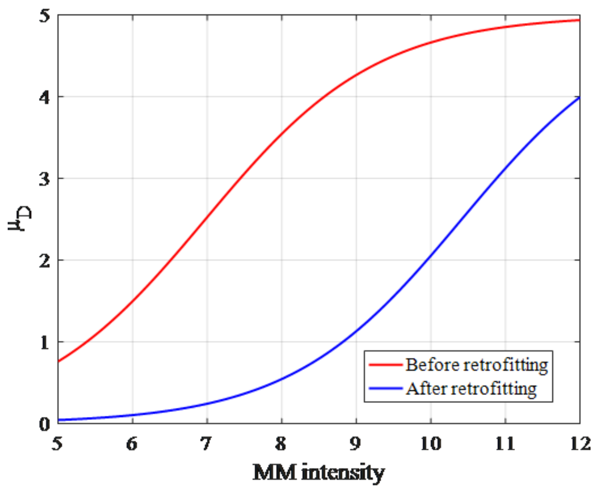


Figure 4: Macroseismic vulnerability curves for tiered temples before and after retrofitting

6. Conclusions

This research explored the quantified analysis of the seismic vulnerability of multi- tiered temples of Kathmandu Valley, adopting Macroseismic method applied in the before and after 2015 Gorkha earthquake scenario construction, depicting the subsequent variation in construction materials and cost due to incorporation of seismic enhancement measures in reconstruction phase. The major conclusions of the research includes, the significant reduction in the seismic vulnerability of the tiered temples could be achieved by adopting the strategic seismic retrofitting measures up to **68.96%** in average. While, the subsequent increment in the material and cost remained considerably low to achieve the reduction in the corresponding damage level of the temples, which was found to be fairly low, that of only **3.65%** of increment in average.

Furthermore, this research provides a vulnerability model which enables to forecast the probable damage distribution for a given intensity of earthquake which can be helpful for the policy makers in the planning of the future projects regarding necessary material and cost adjustments in order to reduce the seismic vulnerability of the temple structure involving the restoration and reconstruction of tiered temples built in traditional materials and technology. Moreover, further research to address the gap and limitation of this method can be pursued in the future.

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