Proceedings of 10th IOE Graduate Conference
Peer Reviewed
ISSN: 2350-8914 (Online), 2350-8906 (Print)
Year: 2021 Month: October Volume: 10

Structural Suitability of Masonry Structure for Residential Buildings in Rural Areas of Nepal

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Abstract

Construction of masonry structures using different kinds of masonry units is still widely in practice in the rural area and suburban part of Nepal. For the suitability of the building and its implementation evaluation of seismic performance is required. Its affordability and use of local material in construction also governs the suitability of structure in different location. For this four building of different typologies based on reconstruction in 32 districts after Gorkha earthquake were considered for the analysis. These typologies were selected on the basis of HRRP 2018 report[1]. These buildings were modelled using finite element software and analysis by using linear dynamic analysis. Three time histories (Gorkha, Imp Valley and Kobe) were used for the linear dynamic analysis and fragility curve were generated. These fragility curve were compared to understand the seismic performance characteristic of the selected structural system. Material and labor required for building were estimated and total cost of selected building system were calculated.

Keywords

Building Typology, Masonry Building, Time History Analysis, Seismic Performance

1. Introduction

Masonry is an important construction material to build the different residential as well as public buildings in most of the rural and periphery of an urban area of Nepal. A great number of national heritage structures were made of masonry and some of them was survived in past earthquakes also. In most of the rural areas of Nepal, the construction of modern RCC structures are not possible due to many constraints like a fund, availability of materials and skilled workmanship. Therefore, the construction of masonry buildings is the only option in the rural areas of Nepal. A huge amount of resources and funds is invested annually in the housing sector in the rural and urban areas of Nepal. So, there is a need to study the different materials and typologies for future use.

The high cost of building construction is a major problem for low-income groups. One alternative solution for this problem is to maximize the use of local materials and discover new alternative materials that reduce the construction cost. Also, the structure should be sound, safe and provide functional requirements. Affordability, acceptability, and ease in implementation should perhaps be some of the criteria for selecting the concepts for scientific researches [2]. So, the aim of this research is to know the seismic performance of different typologies of buildings and to know the affordability and use of local material in different types of housing typologies that are suitable for rural areas of Nepal.

2. Objectives and methodology

The objective of this research is to determine the seismic performance of masonry structures excited by different ground motions and to determine the suitability of masonry structures in terms of seismic performance, cost and use of local material. For the analysis of building the various literature related to a building typology, material properties, modelling approach and analysis technique was done. After that suitable building typology was selected on the basis of typologies used in different 32 districts after the Gorkha earthquakeThese typologies were selected on the basis of HRRP 2018 report [1]. The report shows that 63.3% buildings were stone with mud mortar, 16.7% buildings were cement mortar brick masonry, 3.5% were cement mortar stone and 6% other typologies. The other represent block and hybrid masonry. To represent block masonry CSEB block was selected for rural area. So, on the basis of this data four typologies were selected. The plan and elevation of these four typologies of building is based on number of household in rural area. CBS 2012 shows that more than 50% of households in rural areas have 4-6 members. The size of the building considered in this research is based on the number of members in the household that is suitable for 4 to 6 members. So, four number of building (one for each typology) with six rooms were choosen for modelling. These four typologies were modelled by finite element software. Maximum displacement at the top storey and base shear of the building was obtained by using time history analysis. Three earthquakes were used for time history analysis.

A fragility curve was obtained to know the probability of failure by a different earthquake. After that result obtained from the analysis was compared to know the performance characteristics of the selected building. Materials were estimated by using standard norms and cost of each building was calculated. Materials were divided into local and commercial material and percentage of local material in terms of cost was determined to obtain the use of local material in different typologies.

3. Building Description

Four building typologies with a similar plan are considered [1]. The building is two storey and the storey height of each typology is 2.75m. The room size of each typology is same where the thickness of the wall is different according to NBC-202 (2015), NBC-203 (2015). The standard norms and specifications for CSEB block is as per [3]. The detailed description of building typology considered in this research are:
Brick masonry with Cement mortar (BCEM)
Stone masonry with Cement mortar (SCEM)
Stone masonry with mud mortar (SMUD)
Cement mortar CSEB blocks (CSEB)

Table 1: Building Description

Building Type	Length (m)	Breadth (m)	Wall Thickness(mm)
BCEM	8.72	4.56	230
SCEM	9.2	4.8	350
SMUD	9.6	4.9	450
CSEB	8.76	4.58	240

3.1 Material Properties for analysis

For Brick masonry with Cement mortar [4]
Young's modulus (E_m) = 2703.2 N/mm^2
Shear modulus (G) = 915.1 N/mm^2
Poisson's ratio(υ) = 0.32
Unit weight(Υ) = 18.85 KN/m^3

For coursed rubble stone masonry cement mortar [5]
Young's modulus (E_m) = 2550 N/mm^2
Shear modulus (G) = 840 N/mm^2
Poisson's ratio(υ) = 0.25
Unit weight(Υ) = 22 KN/m^3

For Coursed rubble Stone Masonry with mud mortar [6]
Young's modulus (E_m) = 502.19 N/mm^2
Shear modulus (G) = 209.2 N/mm^2
Poisson's ratio(υ) = 0.2
Unit weight(Υ) = 17 KN/m^3 [7]

For CSEB [8]
Young's modulus (E_m) = 851 N/mm^2
Shear modulus (G) = 354 N/mm^2
Poisson's ratio(υ) = 0.2
Unit weight(Υ) = 17.65 KN/m^3

For timber [9]
Weight per unit volume(Υ) = 8.05 KN/m^3
Modulus of elasticity (E) = 12600 N/mm^2
Poisson ratio(υ) = 0.12

3.2 Modelling

The macro-element model does not make a distinction between individual units and joints but treats masonry as a homogeneous anisotropic continuum [10]. This model is a macroscopic representation of a continuous model in which the parameters are directly correlated to the mechanical properties of the masonry elements [11]. The different typologies of the building were modelled by assembling wall elements together. Masonry walls of thickness 230mm to 450mm were simulated by thin bi-dimensional elements (shell elements) considering only in-plane behavior.

The timber beam was modelled by assigning the properties of timber and modelled as three dimensional beam element. The connection of the timber floor/roof with the masonry wall was assumed that it was simply resting on the wall because the timber nails or iron ties, if present, were heavily deteriorated or damaged over the long years [7]. The base of the model is assumed to be fixed. Horizontal bands such as sill, lintel and floor bands were modelled as frame elements. Different parts of the roof like a rafter, purlin, roof post, ridge beam were modelled as frame elements by assigning the properties of timber. The vertical bar used in the corner and T junction were modeled as a frame element and designed section with solid sections. The detailed description of different frame elements as per NBC 202-2015 and NBC 203-2015 are shown in Table 2:

Table 2: Section Properties according to NBC 202-2015 [12] and NBC 203-2015[13]

S.N	Element	Size
1	Timber Floor Beam	240mm*120mm
2	Band	75mm*wall thickness
3	Rafter/Purlin	120mm*65mm
4	Roof Post	120mm ϕ
5	Ridge Beam	120mm*65mm
6	Vertical Reinforcement	12mm ϕ

Live load on the floor was taken as 2 KN/mm^2 and Gravity load was calculated on the basis of the unit weight of different materials. The roof load depends on what type of roofing is used. Based on the past research roof load is taken as 1.5 KN/mm^2. The plan and modelling of building is as shown in figures 1-3. The plan and elevation of other typologies were same and the wall thickness and masonry properties were different.

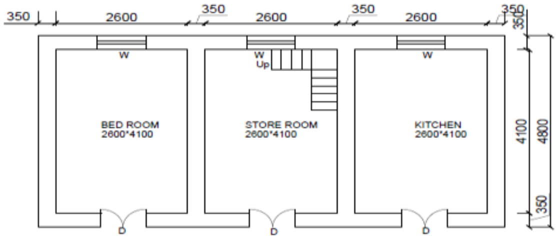

Figure 1: Ground floor plan of SCEM typology

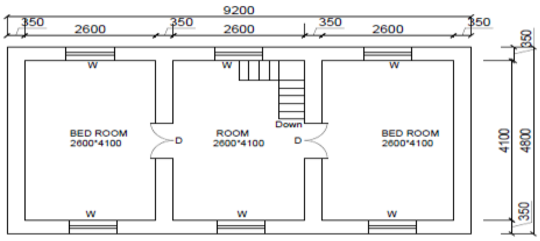

Figure 2: First floor plan of SCEM typology

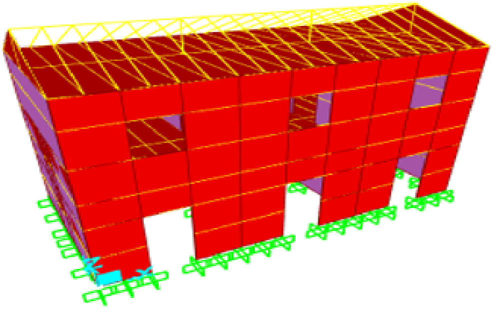

Figure 3: Finite element model in SAP2000

4. Analysis

After completion of modelling, modal analysis was performed. Since a single record is not sufficient to describe the behaviour of the structure, a sufficient number of records is required [14]. Linear time history analysis was performed for three earthquakes by varying PGA. The three different earthquakes were Gorkha earthquake with PGA 0.1634g, Imp Valley earthquake with PGA 0.2808g, Kobe earthquake with PGA 0.3447g. These earthquakes were rescaled at 0.2g, 0.3g, 0.45g, 0.6g, 0.75g, 0.9g, and 1g so that a fair comparison can be made. By linear time history analysis maximum displacement and base shear were calculated.

Damage evaluation was carried out using the fragility function that is given as lognormal distribution in which a spectral displacement is applied as a stochastic variable. A method suggested by HAZUS is adopted to generate fragility curve. A basic equation is[15]

$$P_{\mathrm{f}} = \phi\left(\frac{ln(\frac{S_{\mathrm{d}}}{S_{\mathrm{c}}})}{\beta}\right) \tag{1}$$

Where P_f is the probability of failure, ϕ is the Operational calculus for obtaining the cumulative standard normal distribution function, S_d and S_c are demand and capacity displacement, β is the log standard deviation that represents total uncertainty. Four damage states (slight, moderate, extensive and complete) are used as the capacity of the building [16].

5. Results and Discussion

The four representative buildings were modelled using the finite element modelling concept. Then Modal and linear time history analysis was performed for the response of the selected buildings. These four buildings are of different mechanical properties and wall thickness but all of them have the same room size. The results were in terms of maximum (top) displacements and base shear. The time period of the BCEM typology was found to be 0.143 sec. Similarly the time period of SCEM, SMUD and CSEB were found to be 0.146, 0.175 and 0.168 sec respectively. The fragility curves of each building with four damage states namely slight, moderate, extensive, and complete for three earthquakes: Gorkha, Imp valley, and Kobe are demonstrated. After that cost of different typology was calculated using Ramechhap district rate.

5.1 Displacement

Lateral displacement of BCEM typology at PGA 0.4g for Gorkha, Imp Valley and Kobe earthquake was 2.462mm, 3.242mm and 5.219mm. Lateral displacement of SCEM typology at PGA 0.4g for Gorkha, Imp Valley and Kobe earthquake was 3.281mm, 6.034mm and 7.231mm. Similarly, Lateral displacement of SMUD typology at PGA 0.4g for Gorkha, Imp Valley and Kobe earthquake was 5.786mm, 10.455mm and 12.020mm. Lateral displacement of CSEB typology at PGA 0.4g for Gorkha, Imp Valley and Kobe earthquake was 3.962mm, 7.497mm and 10.809mm. Similarly displacement and drift at different PGA for each earthquake and typologies were determined. For the same PGA value of different earthquake data is found to be different for same building which is due to parameters associated with time history function like frequency content and duration.

Result shows that Lateral displacement and storey drifts are considerably reduced while the contribution of brick wall with cement mortar (BCEM) is taken into account. This shows that characteristics of masonry walls influence the overall behaviour of structures when subjected to lateral force.

5.2 Base Shear

The base shear of all four typologies of building varies linearly with an increase in PGA (g). This is due to linear time history has shown all parameters vary linearly along with Sa/g. The base shear of SMUD typology is highest among the four typologies. The figure 4 to 7 shows that the base shear variation for four typologies for Gorkha, Imp Valley and Kobe earthquake. The variation of base shear for different earthquake is due to parameters associated with time history function like frequency content and duration.

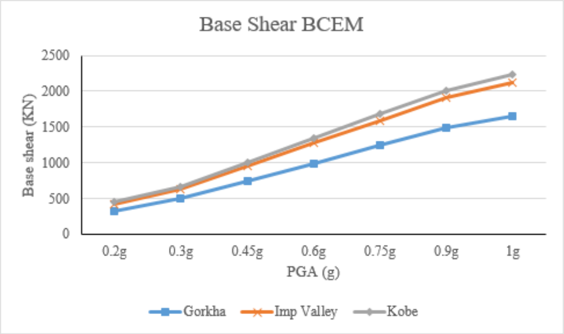

Figure 4: Comparisons with different earthquake time history (BCEM)

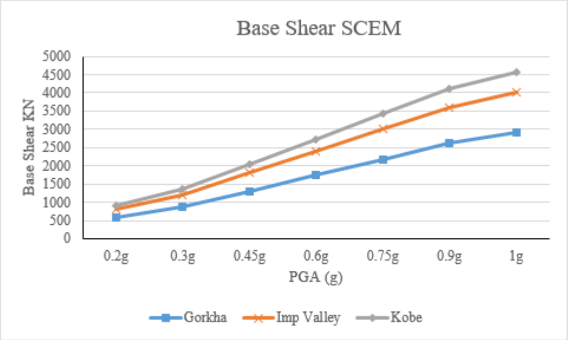

Figure 5: Comparisons with different earthquake time history (SCEM)

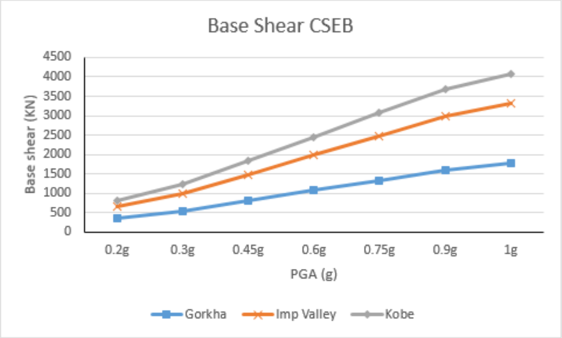

Figure 6: Comparisons with different earthquake time history (CSEB)

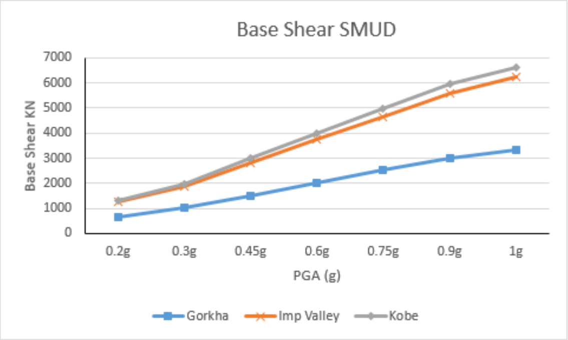

Figure 7: Comparisons with different earthquake time history (SMUD)

5.3 Fragility Curve

According to the seismic hazard analysis map of Nepal, it is shown that PGA for 10% probability of exceedance in 50 years (return period 475 years) is expected to be 0.4g [17]. Therefore, the probability of failure is observed at the PGA value of 0.4g for each type of building. Demand of each earthquake is obtain by linear analysis and capacity of building is obtain from HAZUS 4.2 SP3. Four damage state given by [16] are slight, moderate, extensive, complete.
Slight = $0.7d_y$
Moderate = $1.5d_y$
Extensive = $0.5(d_y + d_u)$
Complete = d_u
Where,
d_y = Yield displacement
d_u = Ultimate displacement
After that fragility curve generated by using equation 1. Since the response due to Kobe earthquake is highest, the probability of failure due to Kobe earthquake is also highest than Imp valley and Gorkha earthquake. Figures 8 to 11 shows that fragility curve for four typologies for Kobe earthquake.

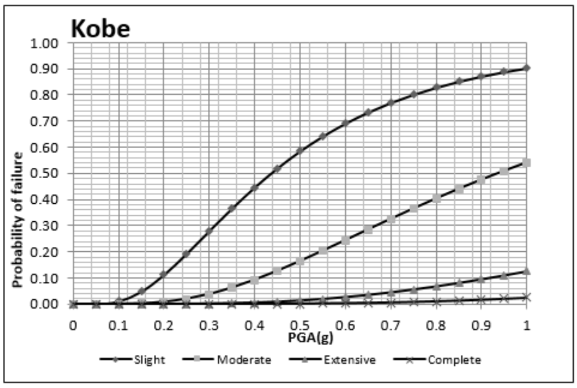

Figure 8: Fragility curve of BCEM typology

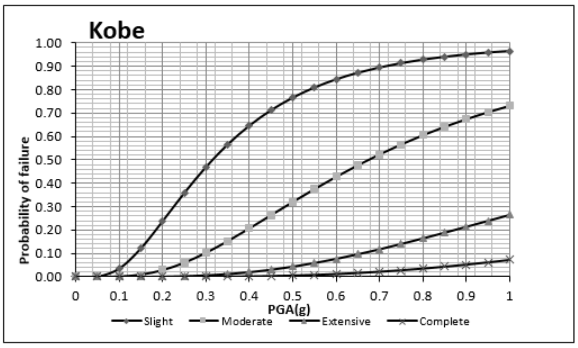

Figure 9: Fragility curve of SCEM typology

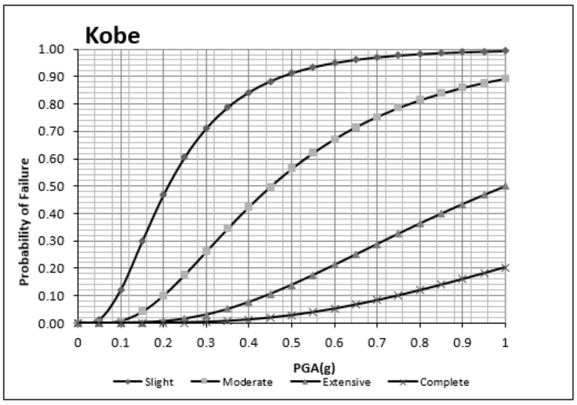

Figure 10: Fragility curve of CSEB typology

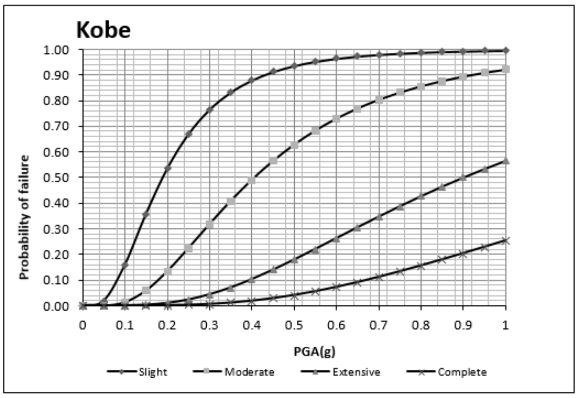

Figure 11: Fragility curve of SMUD typology

5.3.1 Gorkha earthquake as seismic input

Figure 12 shows that the probability of failure of the different building at 0.4g of Gorkha earthquake. Building BCEM has a 9.53% chance of experiencing Slight damage, 0.62% chance of experiencing moderate damage, no chance of experiencing extensive damage and complete damage. Analyzing these probabilities, the building is expected to have no/slight damage state as the probability of failure below 50% in slight damage condition.

Similarly, other types of buildings are also analyzed. Building SCEM, SMUD and CSEB are also expected to have slight damage since their probabilities of failure (19.48%, 51.05% and 28.58%) respectively) at PGA of 0.4g of Gorkha earthquake.

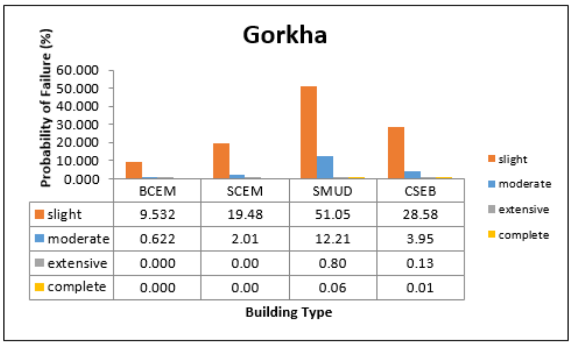

Figure 12: Probability of failure at PGA 0.4g for Gorkha Earthquake

5.3.2 Imp Valley earthquake as seismic input

Figure 13 shows that the probability of failure of the different building at 0.4g of Imp Valley earthquake. Building BCEM has an 18.98% chance of experiencing Slight damage, 1.92% chance of experiencing moderate damage, no chance of experiencing extensive damage and complete damage. Analyzing these probabilities, the building is expected to have no/slight damage state as the probability of failure below 50% in slight damage condition.

Similarly, other types of buildings are also analyzed. Building SCEM, SMUD and CSEB are also expected to have slight damage since their probabilities of failure (53.65%, 82.91% and 66.68%) respectively) at PGA of 0.4g of Imp Valley earthquake.

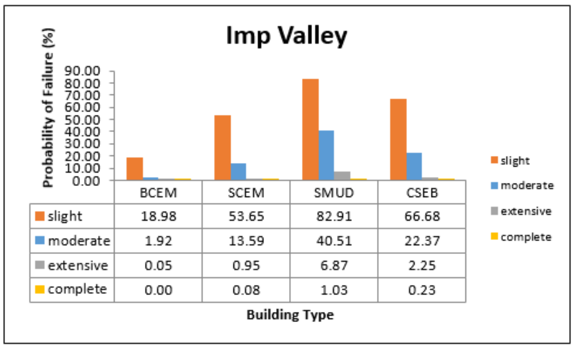

Figure 13: Probability of failure at PGA 0.4g for Imp Valley Earthquake

5.3.3 Kobe earthquake as seismic input

Figure 14 shows that the probability of failure of the different building at 0.4g of Kobe earthquake. Building BCEM has a 44.63% chance of experiencing Slight damage, 9.25% chance of experiencing moderate damage, no chance of experiencing extensive damage and complete damage. Analyzing these probabilities, the building is expected to have no/slight damage state as the probability of failure below 50% in slight damage condition.

Similarly, other types of buildings are also analyzed. Building SCEM, SMUD and CSEB are also expected to have slight damage since their probabilities of failure (64.60%, 87.87% and 84.20%) respectively) at PGA of 0.4g of Kobe earthquake.

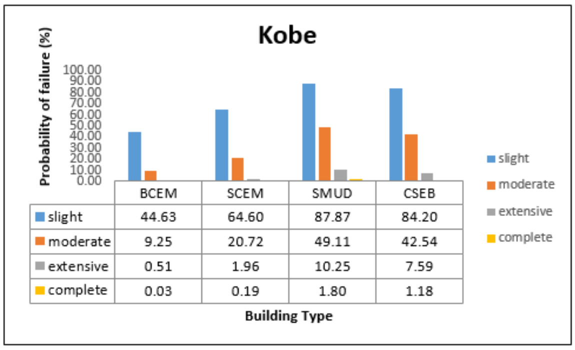

Figure 14: Probability of failure at PGA 0.4g for Kobe Valley Earthquake

5.4 Cost of Labor and Material

Figure 15 shows that the labor cost of SCEM building is highest among four typologies i.e., NPR 8, 15,365.96 and the material cost of BCEM building is highest among four typologies i.e., NPR 10, 71,154.69. The total cost of SMUD building is lowest among four typologies i.e., NPR 12, 42,663.36 which is 13.71% lower than CSEB building, 22.42% lower than BCEM building, and 30.12% lower than SCEM building.

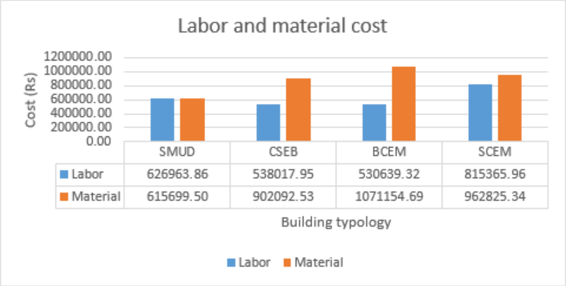

Figure 15: Cost of labor and material for different typology

5.5 Local and Commercial material

In most of the rural areas of Nepal, different building materials like stone, soil, wood, bamboo, and aggregate can be sourced locally whereas brick, cement, rebar, paint, CGI sheet, fixtures for door and roof have to buy from the market. The figure 16 shows that 92.09% of the material can be sourced locally for SMUD building typology. Similarly, 64.95%, 58.79%, and 38.22% of the material can be sourced locally for CSEB, SCEM, and BCEM buildings respectively.

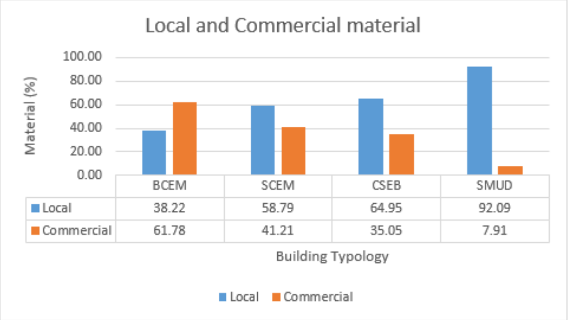

Figure 16: Use of local and commercial material for different typology

6. Conclusion

Four buildings of different typologies and the same floor type and plan were taken for the analysis. The seismic input is taken as three earthquakes (Gorkha, Imperial Valley, Kobe) ground motions histories with varying levels of peak ground acceleration. The response was obtained as maximum top displacement and the fragility curve for each typology have been plotted.

The probability of failure of a different building is a small percentage in the analysis of houses applying the Gorkha Earthquake than the other two earthquakes (Imp Valley and Kobe) histories. Also, the probability of failure of four typologies shows slight damage at 0.4g in Imp valley and Kobe earthquake. Hence the performance of a building by following NBC code and standards can withstand the different types of earthquake-like Gorkha Earthquake with less damage and are suitable in terms of seismic performance. The following major conclusions are drawn from the current research.

- Lateral displacement and storey drifts are considerably less in BCEM typology than that of SCEM, CSEB, and SMUD typology. Characteristics of masonry and thickness of walls influence the overall behavior of structures when subjected to lateral force.
- For the same value of PGA, the displacement value of different earthquake data is found to be different for the same typology.
- For the same earthquake, fragility curves are different for a different typology of buildings due to the variation in material properties and the thickness of the wall.
- For the same value of PGA, the probability of failure due to seismic input Kobe is highest and that of Gorkha is lowest.
- The total cost of SMUD building is lowest among four typologies i.e., NPR 12, 42,663.36 which is 13.71% lower than CSEB building, 22.42% lower than BCEM building, and 30.12% lower than SCEM building. By this we can say that SMUD typology is most economic typology as compared to other typologies.
- In SMUD typology 92.09% (by cost) of material can be sourced locally. Similarly, 64.95%, 58.79%, and 38.22% of the material (by cost) can be sourced locally for CSEB, SCEM, and BCEM buildings respectively. So, SMUD typologies can be constructed using the higher percentage of local material.

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