Сейсмостойкость сооружений
Seismic resistance

Seismic response of stone masonry building with wooden band

Govinda Khatri[1], Govind Prasad Lamichhane[2]*

[1]*Mid-Western University, Post Box 21700, Birendranagar-9, Surkhet, Federal Democratic Republic of Nepal*
[2]*Pokhara University, Pokhara Metropolitan City-30, Lekhnath, Kaski, Federal Democratic Republic of Nepal*
*govindkhec@gmail.com

Abstract

Most stone-masonry structures were built at a time when seismic risk was not considered in their design. Recent moderate to strong earthquakes have confirmed the vulnerability of heritage buildings, especially those constructed with unreinforced-masonry materials in various developing countries, worldwide. Proper assessment of the seismic performance and of the potential deficiency of existing heritage structures forms the basis for determining the degree of intervention needed to preserve their heritage values. Analysis of masonry wall confined by wooden band has been carried out using various structural analysis programs. In analysis appropriately considered and introduced link element such as hook, gap and spring at connecting nodes of vertical and horizontal timber elements. The result shows that the traditional floors and spandrels of the existing structure are the vulnerable parts which need strengthening of them to assure the structural members are able to resist seismic vulnerability. The required improvement and strengthening technique in existing building are proposed and better results are marked. The analysis of the modified structure shows considerably improvement in the dynamic characteristics of the buildings and overall structural response of those.

Keywords: stone masonry, band, band connector, spandrels

Влияние землетрясения на каменную кладку зданий с деревянным поясом

Г. Хатри[1], Г.П. Ламичхане[2]*

[1]*Средне-Западный университет, Федеративная Демократическая Республика Непал, Суркхет, Birendranagar-9, п/я 21700*
[2]*Университет Покхары, Федеративная Демократическая Республика Непал, Каски, Лекхнат, Pokhara Metropolitan City-30*
*govindkhec@gmail.com

Аннотация

Большинство каменно-кладочных сооружений строилось во времена, когда при их проектировании сейсмический риск не учитывался. Недавние средние и сильные землетрясения показали уязвимость ветхих зданий, особенно построенных из неармированных каменных материалов в развивающихся странах по всему миру. Цель настоящего исследования – оценить сейсмические

Govinda Khatri, lecturer of the Faculty of Engineering.
Govind Prasad Lamichhane, Dean in Mid-Western University, Associate Professor of the Faculty of Science and Technology, PhD in Technical Sciences.
Хатри Говинда, преподаватель Инженерного факультета.
Ламичхане Говинд Прассад, декан Средне-Западного университета, доцент факультета науки и техники, кандидат технических наук.

характеристики и потенциальные возможности существующих каменных, кирпичных строений. Для этого определялась степень укрепления строений, необходимого для сохранения их как бесценного наследия прошлого. Изучение кладки стены, ограниченной деревянной лентой, проводилось с использованием различных программ структурного анализа. Соответствующим образом рассмотрены и введены звенья таких элементов, как крюк, зазор и пружина, в узлах соединения вертикальных и горизонтальных деревянных элементов. В результате выявлено, что традиционные полы и своды существующих конструкций являются уязвимыми и нуждаются в укреплении, чтобы гарантированно противостоять землетрясениям. Предложены необходимые методы улучшения и укрепления существующих зданий. Анализ модифицированной конструкции показывает значительное улучшение динамических характеристик зданий и их общей конструктивной характеристики.

Ключевые слова: каменная кладка, пояс, врубка, свод

1. Introduction

The historical and traditional structures of Karnali Zone of Sinja Valley (Nepal) are constructed with excessive use of stone masonry and timber elements. Even today, use of masonry walls cannot be avoided in developing countries, worldwide like our country. The timber elements are used in these houses in the form of beams, columns, joists, doors, windows, band and band connectors and other decorative elements [1]. Timber door, windows and other decorative elements not only provide pleasant aesthetic view but also impart structural stability and in controlling localized stresses. However, the structural strength of these houses against the possible earthquakes is limited. The situation calls for the need of seismic analysis of the buildings so that appropriate strengthening techniques can be applied. Stone masonry house are highly vulnerable in shear, bending, and torsions. Due to these stress on masonry, out of failure and in plane failure is common vulnerable phenomenon. The appropriate modeling of the building like those of stone masonry is important to assess in analysis for performance and response of the structure [2].

As per field observation, most of houses of Karnali Zone (Nepal) made of stone masonry with compacted mud thatched roof. Buildings are not designed properly in terms of seismic performance and vulnerability. Besides that Karnali Zone (Nepal) by the virtue of active faults in the vicinity, several places worldwide are located in highly seismic prone zone, constructed highly steep terrain and the soil strata is found composed of very weak soil. The structures constructed over such terrain and with soft strata are not very much favorable for resisting seismic forces, which may subject to high amplification of ground shaking effect [3].

The most area of Sinja Valley (Nepal) still contains traditional building constructed with masonry and timber. Neither significant researches nor have detailed studies of the loads or bearing capacities of traditional houses of Sinja Valley been carried out. Usually, most of the construction or repair works are done in a very simple way without considering seismic effects [1–6].

A lot of research works have been conducted on new construction materials and technologies but the research works regarding retrofitting, rehabilitation, repair, strengthening of traditional house are limited. Besides that this tradition also affects the cultural heritage housing construction practices and lose our traditional architectural value day by day.

In view of structural performance masonry structures have limited resisting capacity against earthquake (Figures 1 and 2) [7]. So, it is vital to have a study to address the present status of the structural capacity of the traditional house whether they are capable of withstanding the possible future seismic impact. The responsibility of a structural engineer is not only limited to construction of modern structures, but also to preserve the traditional structures which reflect the state of civilization, tradition and culture [8; 9]. In this regard, the present study becomes an essential step in the strengthening of traditional house for our future generations and the study of the Sinja Valley (Nepal) housing trend [10; 11]. Likewise the analysis is done enhancing seismic impact worldwide.
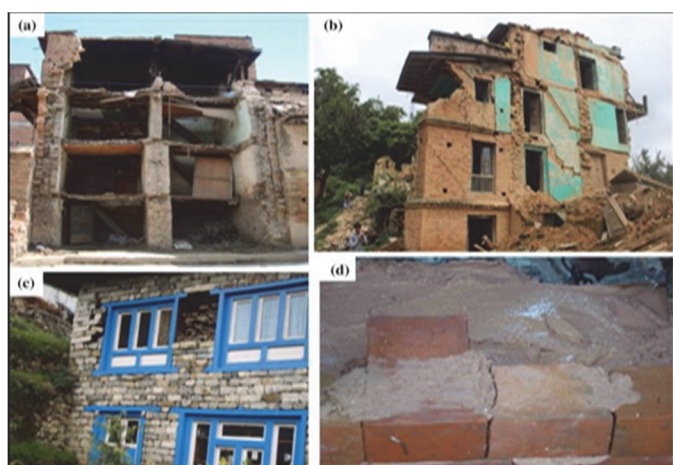
Figure 1. Failure mode of masonry houses:
a – out of plane collapses of load bearing masonry wall in Bhaktapur;
b – heavily damaged masonry structure in Chautara due to out of plane collapse
of majority of walls; *c* – delaminating of the masonry observed in stone masonry wall
in Solukhumbu (Everest base camp area); *d* – common practice
of mortar placement for masonry construction [12]

Figure 2. Failure mode of masonry houses:
a – pounding and progressive failure on the building situated on edge;
b – complete collapse of row houses in Baluwa (near epicenter;
c – progressive failure on row houses and good performance of timber frames;
d – stone masonry failure

2. Methods

The research plan is shown in Figure 3.

The traditional building as shown in Figures 4 and 5 is usually rectangular in plan and stretched over two storey's height. The length of the plan is 7.7 m with facades of various widths but most 6.92 m, the house is raised vertically over two storeys with a partition wall running up the height, creating front and back rooms. Timber frames are provided at certain interval 1.7 m, parallel to the facade. Sometimes timber frames are replaced by stone walls in order to create rooms. The typical inter storey height is between 1.75 m for ground floor and 2.75 m for first floor. The ground floor is used for animals and first floor is used for human beings. Generally small size of opening are provided where size of doors are 0.90 m width and 1.5 m height whereas window size are 1.2 m width and 1 m height. During the construction, the modern construction materials like concrete, bricks, steel were not available in the proposed site frequently [1].
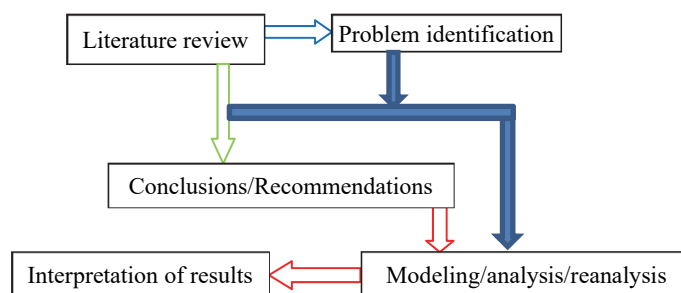
Figure 3. Flow chart of methodology

Using structural analysis program it's not easy to create model as in RCC or steel building. However using various links emends the model of masonry building shall be created whose applications are as followings [13]:

1) the links as hooks, springs, plastic wanes are created so as to meet criteria of nodal points among joist and beams, beams and posts stone masonry walls and stiffening beams and connectors;

2) those links need for optimizations of modal so as give approximate final output results by nearest partial fixity among all nodes of structures;

3) those links are placed in separate model and the results are verified with manual results;

4) the main applications of such links are to create partial fixity and pinned joints among nodes and stone masonry with connectors and stiffened beams.
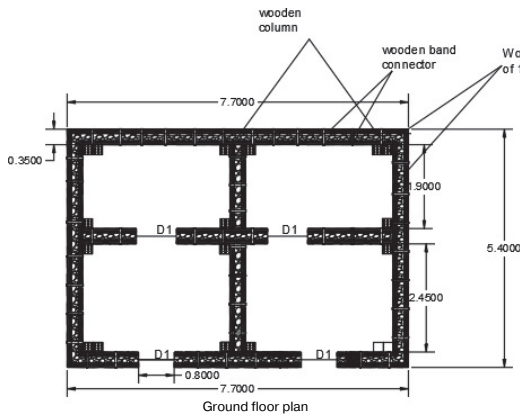
Figure 4. Ground floor plan of model house
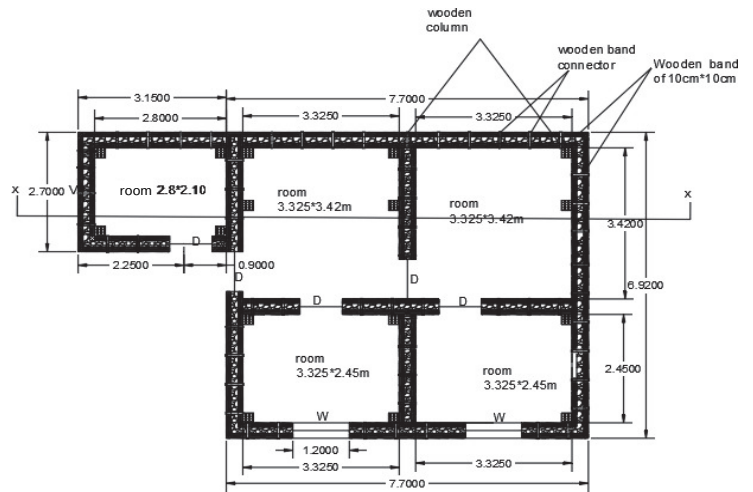
Figure 5. First floor plan of model house

3. Results and discussion

The link element is used to connect two joints together. Each link element may exhibit up to three different types of behaviour: linear, non-linear, and frequency-dependent, according to the types of properties as signed to that element and the type of analysis being perform [14].

Fundamental time period of different models
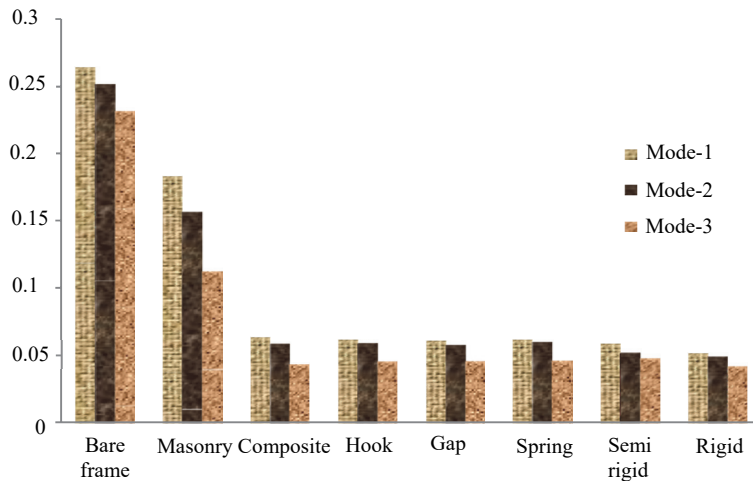
Figure 6. Comparison of period

Fundamental time period of hook, masonry, bare frame, composite, gap, spring and rigid models obtained as 0.0613, 0.183, 0.264, 0.063, 0.0603, 0.061 and 0.051 second respectively (Figure 6). Maximum fundamental time period obtained is in care of bare frame and minimum in care of rigid. There is no significance difference in time period among hook, composite, gap and spring. It can be seen that influence of timber band is significant to increase global lateral stiffness of the building that caused de-

crease in fundamental time period in hook, composite, gap and spring. Band is not modeled inn care of bare frame and masonry care. Similarly rigid diaphragm also play significant role for enhance the stiffness of the building [15]. Base shear data presented at Tables 1–4 and Figures 7–9.

Table 1

Base shear calculation, manually

Description of items	*L*, m	*B*, m	*t*, m	Unit weight, kN/m³	Weight, kN
Storey height, m, ground floor			1.5		
Thickness of mud, m			0.2		
Plank thickness			0.05		
Thickness of wall			0.35		
Size of joist		0.18	0.2		
Size of beam		0.2	0.225		
Size of post		0.225	0.225		
Total longitudinal length	7.7				
Total transverse length	6.92				
Unit weight of mud				15	
Unit weight of wood				8.5	
Unit weight of stone masonry				22	
Load calculation					
Mud load calculation					159.85
Self weight of plank					22.646
Weight of joist					21.175
Weight of beam					11.781
Weight of post					23.237
Weight of wall longitudinal					592.9
Weight of transverse wall					399.63
Seismic load due to live load					26.642
Total lumped mass at roof					1231.2
Total lumped mass					1257.9
Total weight, *w*					2789.1
Time period					0.15
Importance factor					1
Response reduction factor					1.5
Sa/g					2.5
Aₕ					0.0970
Vᵦ					156.73

Table 2

Comparison of base shear

Model designation	Base shear along *X*-direction, *Vx*, KN	Base shear along *Y*-direction, *Vy*, KN
Gap	158.81	171.12
Hook	153.38	159.90
Bare frame	31.28	25.10
Masonry	144.85	110.67
Composite	153.38	159.90
Spring	138.58	146.39
Semi rigid	155.22	162.39
Rigid	156.10	170.10
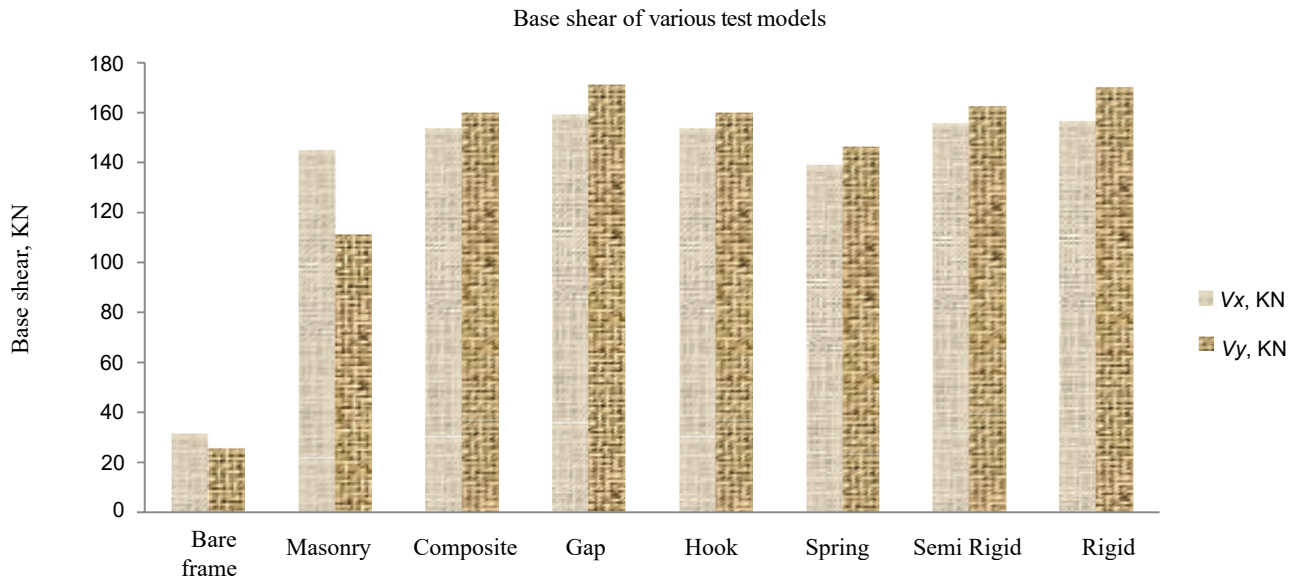
Figure 7. Base shear of various test models
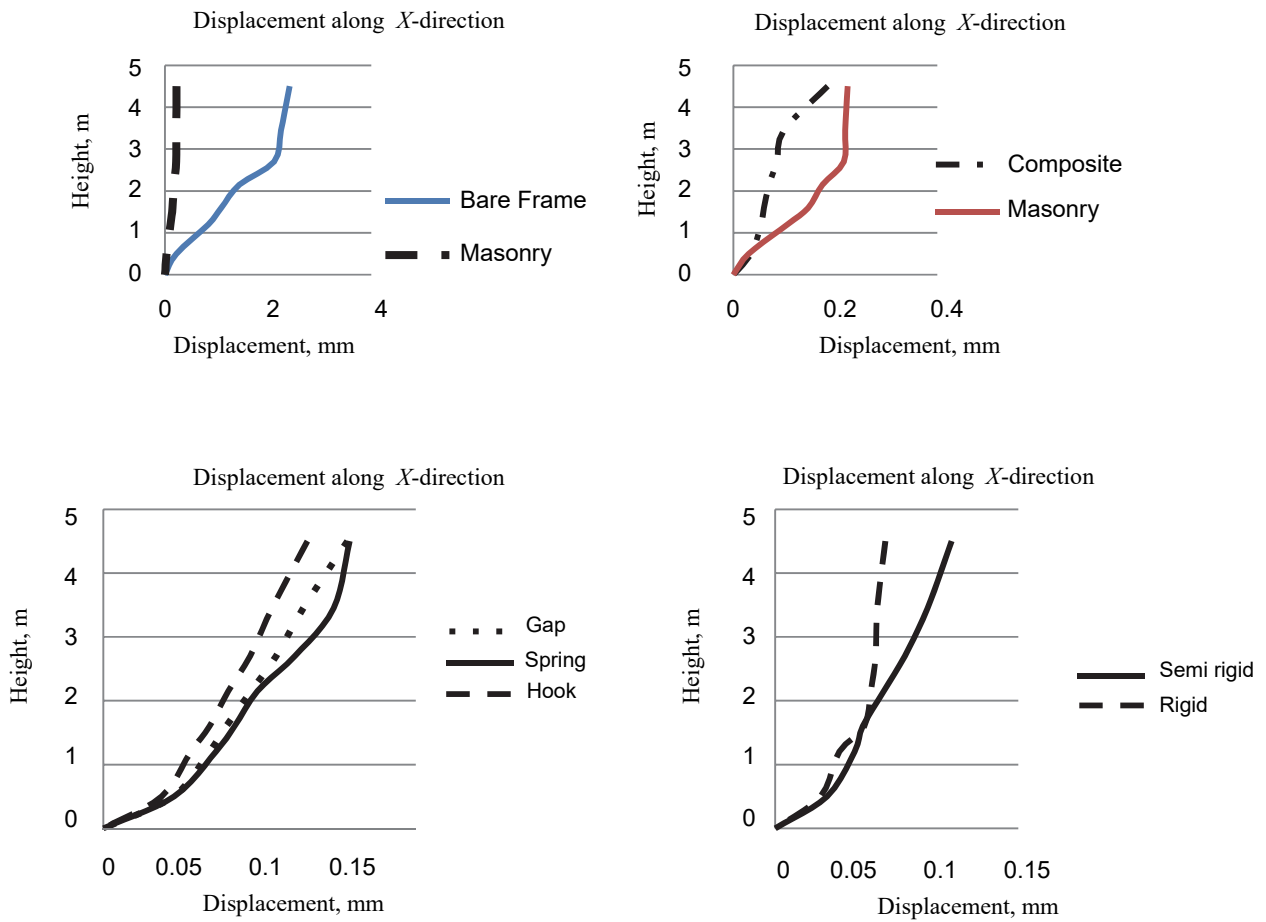
Figure 8. Displacement about *X*-axis of various modeled cases

Table 3

Displacement about *X*-axis, mm

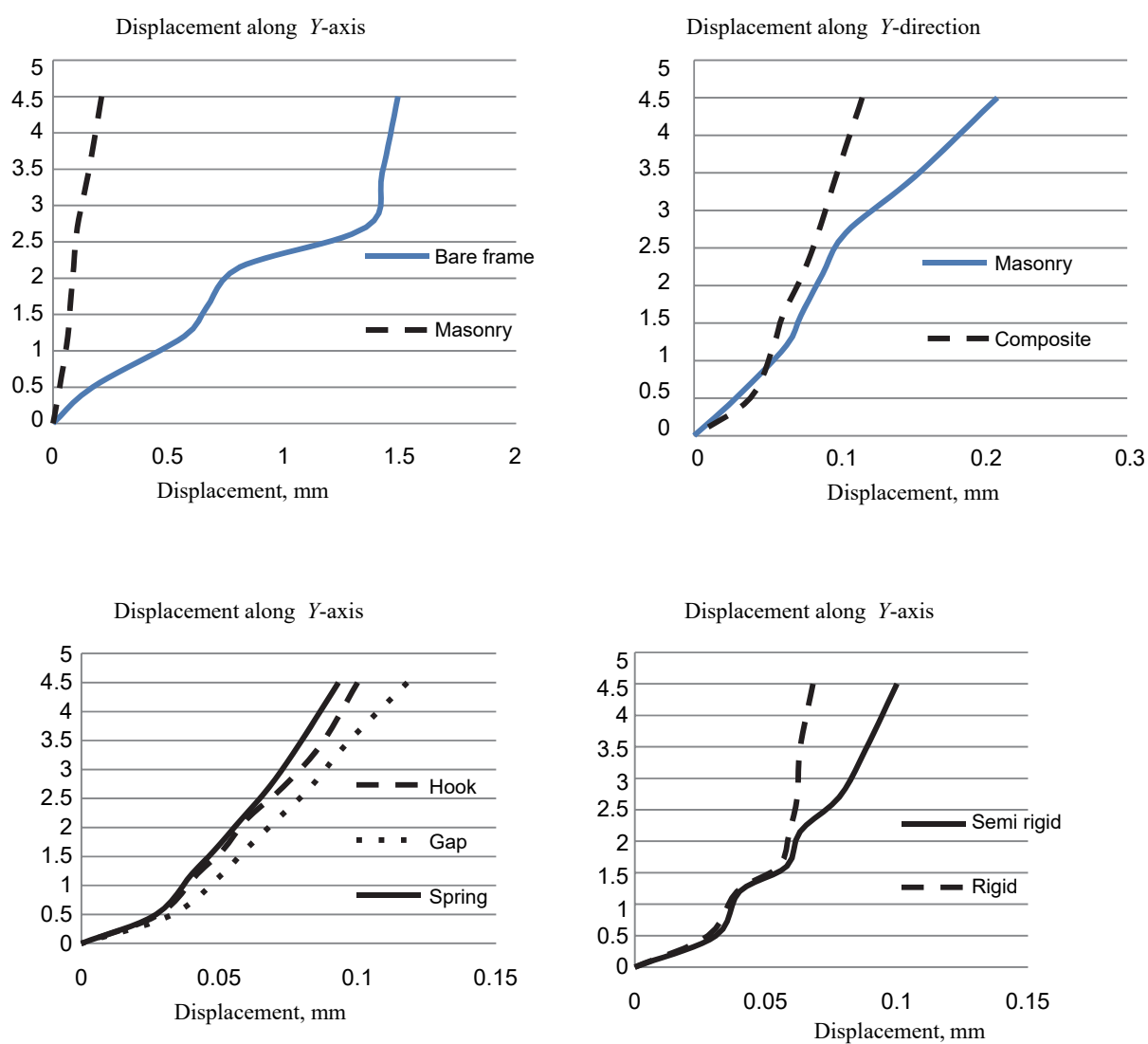| Joint	Height, m	Bare frame	Masonry	Composite	Hook	Gap	Spring	Semi rigid	Rigid
720	4.5	2.416	0.224	0.185	0.098	0.1172	0.1183	0.1089	0.068
754	3.45	2.251	0.219	0.099	0.081	0.096	0.1106	0.094	0.063
11	2.7	2.1166	0.2165	0.085	0.0705	0.083	0.092	0.08	0.062
13	2.15	1.4436	0.1748	0.070	0.06	0.071	0.074	0.067	0.059
146	1.6	1.092	0.1467	0.060	0.051	0.059	0.063	0.054	0.055
15	1.2	0.84	0.106	0.054	0.042	0.051	0.054	0.049	0.0395
145	0.5	0.22	0.0298	0.035	0.028	0.0336	0.034	0.032	0.028
38	0	0	0	0	0	0	0	0	0

Figure 9. Displacement about *Y*-axis of various modeled cases

Table 4

Displacement about *Y*-axis, mm

Joint	Height, m	Bare frame	Masonry	Composite	Hook	Gap	Spring	Semi rigid	Rigid
720	4.5	1.49	0.21	0.116	0.1	0.117	0.096	0.1	0.059
754	3.45	1.422	0.153	0.098	0.08	0.096	0.079	0.088	0.063
11	2.7	1.352	0.105	0.086	0.07	0.083	0.068	0.078	0.062
13	2.15	0.805	0.089	0.075	0.06	0.071	0.058	0.063	0.059
146	1.6	0.664	0.074	0.061	0.05	0.059	0.048	0.058	0.055
15	1.2	0.567	0.064	0.055	0.04	0.051	0.04	0.04	0.039
145	0.5	0.171	0.029	0.039	0.03	0.033	0.027	0.031	0.028
38	0	0	0	0	0	0	0	0	0

Output of shell element internal stresses. The basic shell element stresses are identified as S11, S22, S12, S13, and S23. You might expect that there would also be an S21, but S21 is always equal to S12, so it is not actually necessary to report S21. S*ij* stresses (where *i* can be equal to 1 or 2 and *j* can be equal to 1, 2 or 3) are stresses that occur on face *i* of an element in direction *j*. Direction *j* refers to the local axis direction of the shell element. Thus S11 stresses occur on face 1 of the element (perpendicular to the local 1 axis) and are acting in the direction parallel to the local 1 axis (that is, the stresses act normal to face 1). As another example, S12 stresses occur on face 1 of the element (perpendicular to the local 1 axis) and are acting in the direction parallel to the local 2 axis (that is, the stresses act parallel to face 1, like shearing stresses). The Figure 10 shows examples of each of these basic types of shell stresses. Structural analysis program reports internal stresses for shell elements at the four corner points of the appropriate face of the element [15].
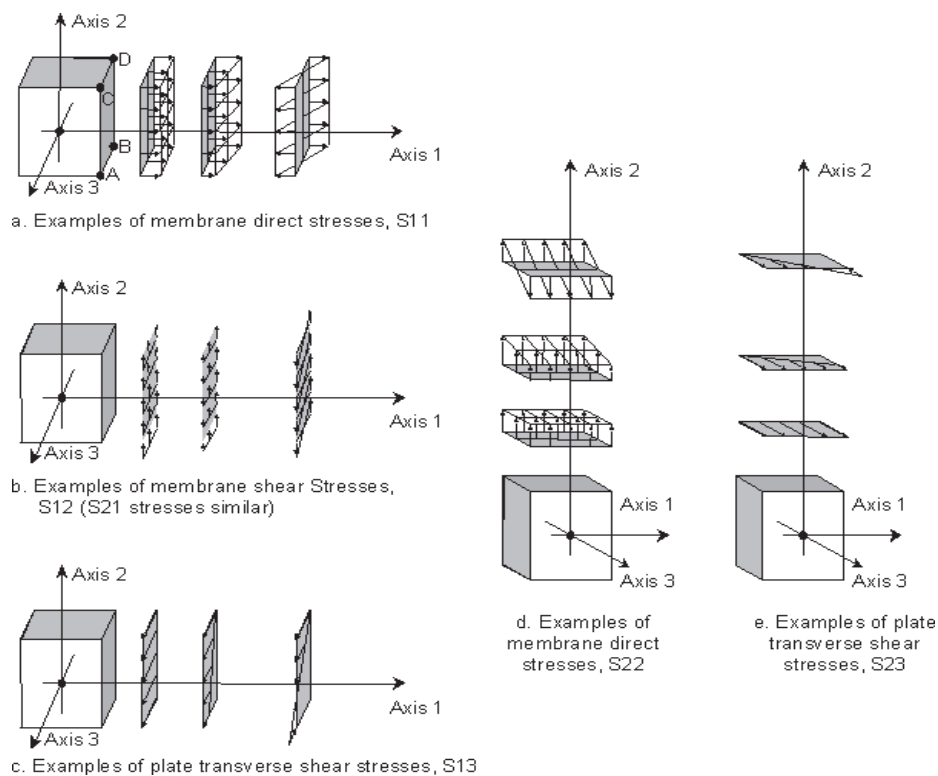

Figure 10. Stresses on thick shell elements

Table 5

Stress at various members and links of building

S.N.	Stress	Bare	Masonry	Composite	Gap	Hook	Spring	Rigid, N/mm²	Frame
1	S11	T	24.19	20.347	6.531	6.594	6.581	6.58	6.134
		C	−22.81	−19.391	−4.866	−4.84	−4.36	−4.867	−5.82
2	S22	T	34.83	20.027	8.923	6.422	6.536	6.54	6.061
		C	−33.02	−19.531	−4.953	−3.81	−3.89	−3.896	−5.806
3	S12	T	0.78	5.275	0.855	0.754	0.762	0.762	0.584
		C	−0.623	−4.849	−0.922	−0.93	−0.93	−0.932	−0.579
4	S13	T	0.561	0.273	0.713	0.459	0.46	0.46	0.904
		C	−0.515	−0.512	−3.27	−2.01	−2.04	−2.047	−4.056
5	S23	T	0.683	0.285	1.206	0.86	0.876	0.876	1.406
		C	−0.507	−0.286	−0.806	−0.42	−0.42	−0.428	−1.042

Table 6

Response of test model (natural time period, sec., and displacement, mm)

Description	Time period from model			Time period from IS 1893:2002	Δx	$-\Delta x$	Δy	$-\Delta y$
	Mode-1	*Mode-2*	*Mode-3*					
Bare frame	0.26	0.251	0.231	0.15	3.082	−3.082	1.815	−1.815
Masonry	0.18	0.15	0.11	0.15	0.392	−0.392	0.205	−0.205
Composite	0.063	0.058	0.043	0.15	0.142	−0.142	0.147	−0.147
Hook	0.061	0.058	0.045	0.15	0.151	−0.151	0.164	−0.164
Gap	0.0603	0.057	0.0449	0.15	0.155	0.155	0.182	−0.182
Spring	0.065	0.058	0.045	0.15	0.178	−0.178	0.193	−0.193
Semi rigid	0.055	0.052	0.043	0.15	0.10	−0.10	0.095	−0.095
Rigid	0.051	0.048	0.041	0.15	0.068	−0.068	0.0738	−0.0738

Table 7

Stress on first floor roof, N/mm²

Descriptions	Point 1 corner	Point 2 corner	Point 3 corner	Point 4 corner	Point 5 middle
Bare frame (S11)	0.85	1.12	0.80	1.02	−0.24
Bare frame (S22)	0.091	0.10	−0.13	−0.46	−0.58
Masonry (S11)	0.094	0.121	0.76	0.58	0.309
Masonry (S22)	−0.348	−0.1966	−0.275	−0.368	−0.51
Composite (S11)	−0.33	−0.061	0.105	0.172	0.3772
Composite (S22)	0.884	0.410	0.438	0.660	−0.678
Rigid (S11)	0.192	0.185	0.113	0.097	−0.39
Gap (S11)	0.364	0.757	0.132	0.227	0.098
Gap (S22)	0.382	0.309	−0.104	0.45	−0.350
Hook (S11)	0.362	0.626	0.136	0.220	0.331
Hook (S22)	0.055	−0.0094	−0.152	−0.182	−0.458
Spring (S11)	0.254	0.621	0.173	0.273	−0.028

Table 8

Stress on wall, N/mm²

Descriptions	Point 1 corner	Point 2 corner	Point 3 corner	Point 4 corner	Point 5 middle
Masonry (S11)	0.0281	0.034	0.031	0.030	−0.013
Masonry (S22)	−0.064	0.0203	0.155	−0.1269	0.10
Rigid (S11)	0.010	0.0115	−0.051	−0.0237	0.0055
Composite (S11)	0.0020	−0.0079	−0.0072	0.0017	0.0024
Composite (S22)	0.0051	0.0011	0.0050	0.0093	0.00288

Higher stress found in the connection of timbers, connector inters face and plank area this scenario show that timber members are must responsible for withstand all types of stress of house and increase the seismic performance of the buildings. Among all the model analysis the axial stress along *X*-axis S11 and S22 is found in masonry and bare frame model and in case of gap, hook, composite, rigid and spring model have less (Tables 5–8). It be clearly seen that model with wooden band and band connector having less amount of stress, i.e. wooden member responsible for to counteract out of plane failure and in plane failure.

4. Conclusion

The modified structure having joint connecting elements such as gap, and spring perform better than the existing one but still lacks fulfilling the required purpose hence another modification is made reducing the size of opening and its placement is at center of wall and finally linked elements and connectors are introduced between timber elements in the model also enhanced the better response of the seismic performance and under seismic performance of the structure.

Specific conclusions:

– introduction of timber joist, beam and column in stone masonry house increase the base shear and reduces the time period and increase the stiffness of the structure. Finally, the response of structure against seismic force is improved by using connectors;

– although timber frames and bands enhance the structural performance under seismic excitation in plane and out of plane stresses, where as the major contributing element to withstand external load is stone masonry as load path shown;

– doors, windows, bands and band connector contribute in controlling the localized stress and create the box effect of the house globally and perform the good behaviors under the seismic forces.

From the result it can be conclude that there is different contribution in lateral stiffness of the building model of different connecting element.

References

1. Bothara J., Brzev S. *A Tutorial: Improving the Seismic Performance of Stone Masonry Buildings* (1st ed.). 2011, July. Publication Number WHE-2011-01.

2. Nepal National Building Code (NBC 205, 1994). *Mandatory rules of thumb reinforced concrete buildings without masonry infill.* HMG/Ministry of Housing and Physical Planning, Department of Building, Kathmandu, Nepal.

3. Varum H., Dumaru R., Furtado A.F. Seismic Performance of Buildings in Nepal after the Gorkha Earthquake. *Impacts and Insights of Gorkha Earthquake.* 2017;1(3). https://doi.org/10.1016/B978-0-12-812808-4.00003-1

4. Asteris P.G. On the Structural Analysis and Seismic Protection of Historical Masonry Structures. *The Open Construction and Building Technology Journal.* 2008;(2):124–136.

5. Tena-Colunga A., Abrams D.P. *Response of an instrumented masonry shear wall building with flexible diaphragms during the Loma Prieta Earthquake.* Urbana, Ill: Dept. of Civil Engineering, University of Illinois at Urbana-Champaign; 1992.

6. Asteris P.G., Repapis C., Cavaleri L., Sarhosis V. On the fundamental period of infilled RC frame buildings. *Struct. Eng. Mech.* 2015;54:1175–1200. http://dx.doi.org/10.12989/sem.2015.54.6.1175

7. Nepal National Building Code (NBC 204, 1997). *Un-reinforcement masonry structure.* HMG/Ministry of Housing and Physical Planning, Department of Building, Kathmandu, Nepal.

8. Ministry of Housing and Physical Planning. *A Management Plan for the Introduction of a National Building Code.* UNDP Project No. Nep.88.054-21.03. Kathmandu, Nepal; 1994.

9. National Planning Commission. *Nepal Earthquake 2015: Post-Disaster Needs Assessment. Volume A. Key Findings.* Kathmandu, Nepal; 2015.

10. Indian Standard Code IS 1597-1. *Construction of stone masonry.* New Delhi: Bureau of Indian Standards; 1992.

11. Nepal National Building Code (NBC 203, 2015). *Masonry building design.* HMG/Ministry of Housing and Physical Planning, Department of Building, Kathmandu, Nepal.

12. Gautam D., Rodrigues H. et al. Common structural and construction deficiencies of Nepalese buildings. *Innov. Infrastruct. Solut.* 2016;1:1. DOI 10.1007/s41062-016-0001-3.

13. Ahmad N., Crowley H., Pinho R., Ali, Q. Displacement-based earthquake loss assessment of masonry buildings in Mansehra City, Pakistan. *Journal of Earthquake Engineering.* 2010;14(1):1–14. DOI: 10.1080 / 13632461003651794.

14. Doudoumis I.N., Deligiannidou J., Kelesi A. Analytical modeling of masonry in filled timber truss work. *5th GRACM International Congress on Computational Mechanics.* 2005. Pp. 1–8.

15. Langenbach R. *Stone Masonry in Clay Mortar with Gabion Bands: A report submitted to the Nepal DUDBC.* Oakland: Conservationtech Consulting; 2015. Available from: http://www.traditional-is-modern.net/NEPAL/DUDBC/Conservationtech-GabionBands.pdf (accessed: 12.09.2020).