Canadian Conference - Pacific Conference on Earthquake Engineering 2023
Vancouver, British Columbia
June 25th – June 30th, 2023

Towards More Efficient Seismic Construction Practices in Developing Countries

Chaymaa Kamal-Alaoui[1], Sanda Koboevic[2*]

[1]Master's student, Department of Civil Engineering, Polytechnique Montreal, Montreal, Quebec, Canada
[2]Professor, Department of Civil Engineering, Polytechnique Montreal, Montreal, Quebec, Canada
*sanda.koboevic@polymtl.ca (Corresponding Author)

ABSTRACT

Many international interventions, on financial and technical level, have been deployed in recent decades to improve seismic performance of buildings in developing countries. Nevertheless, significant human losses and important material damages keep occurring. It's becoming increasingly clear that the solution to this situation may reside in the implementation of "appropriate technologies", which incorporate local materials and financial resources, as well as traditional construction methods, in harmony with local culture and values.

The study presented in this paper has been carried out within the scope of the SmartNET project (Seismic Methodologies for Applied Research and Testing of Non-Engineered Techniques), put forward by Smart Shelter Foundation (SSF). The aim of the project, supported by several academic and industrial partners from all over the world, is to improve non-engineered techniques in developing countries, notably in the Himalayan region, and ultimately produce unified and accessible guidelines for their design and construction. A traditional building construction, frequently seen in this region, combines the rubble stone masonry with flexible wooden diaphragm, has been identified as the appropriate technology. To improve its seismic performance, SSF suggests reinforcing the structure by means of horizontal reinforced concrete bands, placed throughout the entire building.

In the first phase of the project, a two-story prototype school building provided by SSF was modeled by different partners, including a team from Polytechnique Montreal, with an objective to identify the most feasible and reliable methods for technical and social environment of developing countries. At Polytechnique Montreal the macro-element discretization based on the equivalent frame approach was applied. An analytical model of the prototype building was built using STKO/OpenSees software. The presence of reinforcement bands was accounted for by adjusting the bending and shear constitutive laws used for spandrels and piers. Seismic response of the building was studied using a pushover analysis and compared against the results obtained by the team from the University of Bristol (UK) which implemented simplified micro-modelling approach. Initial results are promising and indicate that the presence of the reinforced bands improves ductility but have little effect on peak base shears.

Keywords: Appropriate technologies, Developing countries, Stone masonry, Macro-Modelling, Nonlinear analysis

INTRODUCTION

Of all the natural disasters that continually affect the planet, earthquakes are the most devastating. More than 2.66 million people have died due to this disaster in the last century, and nearly 30 million have been left homeless [1]. A recent research reveals that earthquakes are particularly problematic for developing aeras, especially countries in Asia, South America, and Africa [1].

The reasons for this are obvious: developing regions suffer from poverty, high population density, a real lack of technical skills and expertise, and poor-quality building materials. Furthermore, although building codes and standards in developed and developing countries are similar in their specifications, it is found that for a given earthquake, the seismic behavior of modern buildings is different [2]. In developed countries, most structures have seismic responses that meet specifications. On the other hand, those in developing countries often show their seismic fragility and vulnerability. This suggests that the problem is far from being just a technical one, but rather lies in the way these structures are implemented, and the degree to which they conform to developing environment [2].

At a time when scientific development is supposed to be at its peak, the continued loss of human life year after year due to earthquakes is not acceptable. The most telling example is the recent Mw 7.8 earthquake that struck Turkey and Syria, being the deadliest one in the world since the 2010 Haiti earthquake, and the fourth most costly ever recorded [3]. Thus, with the ultimate goal of helping the affected countries recover from the aftermath of the earthquakes and build more effectively in the future, many financial and technical international efforts and interventions have been made. However, the significant human losses and important material damages persist [4].

The reliability of structures has become a topic of the highest priority and a subject of much discussion in recent years [5]. To understand the reasons behind the failure of innovative and advanced methodologies proposed by developed countries, a particular interest is being paid to traditional constructions that have been able to resist different earthquakes in the past [6, 7]. The goal is to analyze the environment where these technologies are implemented, and to adapt them to the socio-economic context of developing countries [2].

In other words, the most pressing need today is to find ‘miracle solutions’ to produce low-cost reliable buildings, especially in rural areas of developing countries. They must be adapted not only to the materials and financial resources available locally, but also to the construction skills, while remaining in harmony with the lifestyle of the local community [5]. Those ‘magic bullets’ may lie therefore in an earthquake-resistant construction approach, inspired from the traditional structures already in place, built with materials that are easily accessible. Hence, the search for ‘appropriate technologies’ becomes nowadays the concern of several foundations and the focus of various organizations around the world [4].

Smart Shelter Foundation (SSF) [8], a non-governmental organization (NGO) active in Nepal and based in the Netherlands, operates along these lines. Through its SmartNET (Seismic Methodologies for Applied Research and Testing of non-engineered techniques) project, which brings together a vast network of researchers and scientists, SSF seeks to improve building practices in this area, known for its high seismic activity, high population density, and overwhelming poverty [9]. The "appropriate technology" proposed by SSF are the rubble stone masonry buildings, with flexible wooden diaphragms [10]. The construction techniques for this type of structures, which are common used in the region, have been transmitted from generation to generation, and thus they are well assimilated by the local community [10]. However, commonly considered "less modern" and therefore more vulnerable to earthquakes, these buildings are gradually being abandoned, giving way to modern concrete and steel structures, whose design and construction leave much to be desired in most cases. Taking this into consideration, SSF suggests an additional reinforcement of its structure, by means of additional horizontal reinforced concrete bands, placed throughout the entire building in order to increase its ductility and improve seismic performance [8].

The present paper aims to characterize the seismic response of archetype two-story building provided by SSF. To do so, the macro-modeling approach has been adopted. The latter is fit for purpose, as SSF looks for solutions that are feasible in a technical and social environment of developing countries, thus requiring less technical and computational efforts compared with other micro-element methods. Mechanical properties used in the study are based on typical values from Nepal that are available for similar typologies such as brick masonry with mud mortar [11] as well as stone masonry with mud mortar [12]. In order to take into account the reinforcement introduced at the initial design without compromising the frame integrity, an equivalent methodology consisting in modifying the bending and shear constitutive laws of the elements was also treated [13]. The validation of the results obtained is carried out, via the comparison with the results of the University of Bristol (UK) team.

RUBBLE STONE MASONRY: CASE STUDY BUILDING

Template design

The archetype SSF structure is a two-story school building, illustrated in

Fig. 1. It consists of two 3200 mm x 3200 mm rooms and 1400 mm x 6850 mm verandas on each floor. The walls of the structure are 450 mm thick, made of sandstone and rubble with cement mortar joints (30 mm thick), and rise to a total height of 5800 mm (3200 mm on the second floor and 2600 mm on the second floor). The openings are regular with a uniform width of 900 mm. At different levels of the structure, 75-150 mm RC bands are inserted in the walls to improve the seismic response of the building and to provide additional connection between its structural components, resulting in a better stability.

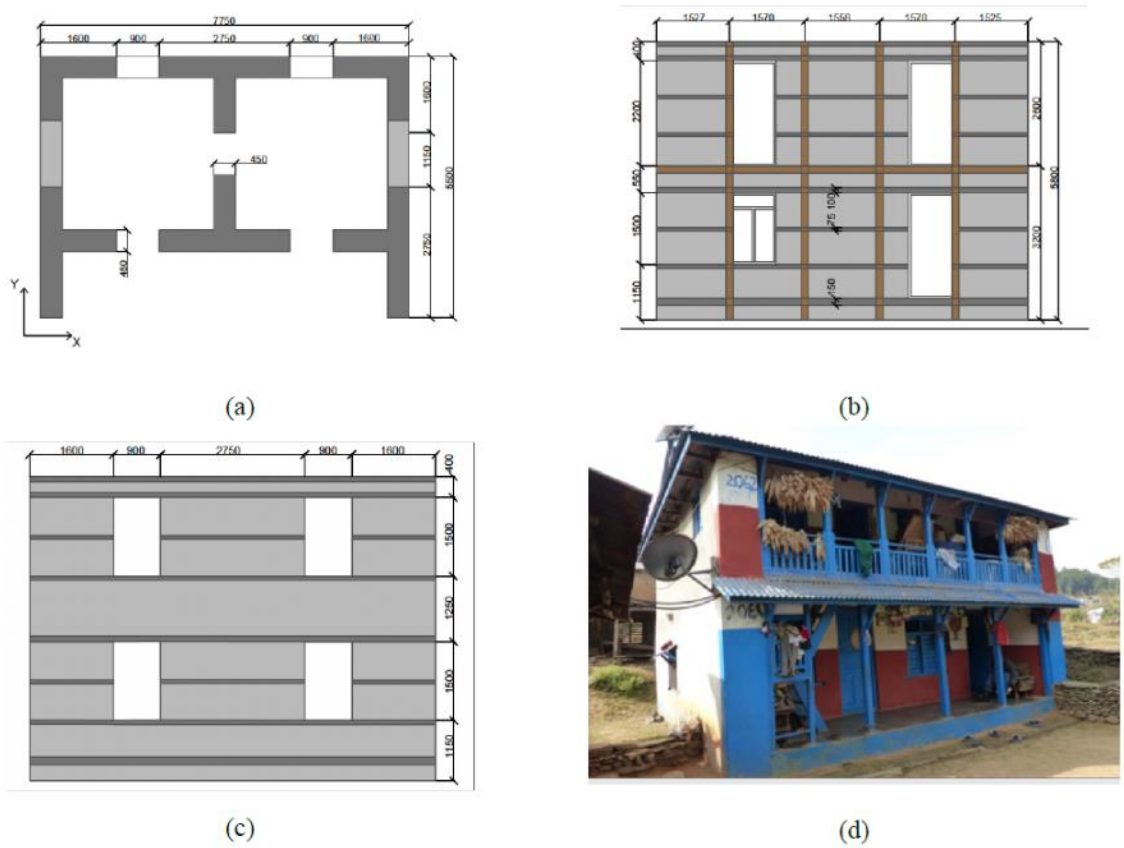


Fig. 1: Two-story Smart Shelter template: (a) plan view of the ground floor; (b) front elevation; (c) back elevation; (d) photograph of a completed building in Nepal.

(adapted from [9]).

The roof and the floor are flexible light diaphragms made of wood. Schildkamp et al. [9] point out that these elements account for only a small portion of the seismic weight, which is primarily concentrated in the load-bearing walls of the structure (97.8%, see Fig.2). Consequently, SmartNet proposes to neglect the presence of the floor and the roof in a preliminary modeling, assuming that they have a small contribution on the seismic behavior of the building.

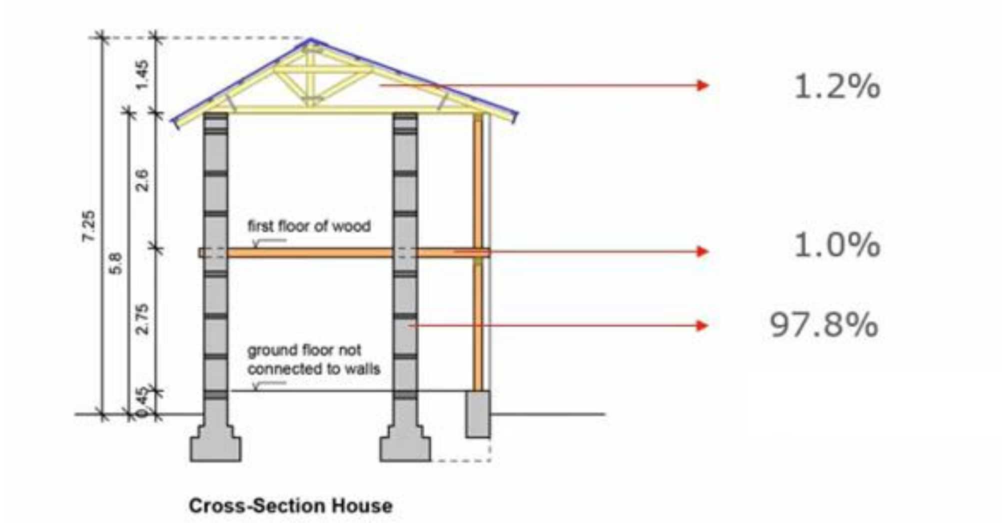


Fig. 2 : Seismic weight concentration in the typical SSF building. (adapted from [8])

Material properties

Rubble stone and mortar are the main construction materials of the studied structure. These local materials are widespread in the region and accessible to all. To accurately model a masonry building, identifying a range of material properties is essential to determine the non-linear material characterization of all structural components.

Produced on site and following traditional techniques, these materials often lack quality and control measures [14]. Defining their mechanical characteristics is a difficult task, requiring numerous experimental studies and sometimes complex laboratory tests. According to an extensive literature review based either in Nepal or in regions nearby such as Pakistan and India, SmartNet defines the mechanical characteristics of these materials as shown in Table 1. The objective is to provide a common data for all teams, so that subsequent comparison could be possible.

Table 1: Mechanical properties of masonry materials. (adapted from [8])

	Rubble stone	**Mortar**	**Concrete**	**Steel**
E (MPa)	25000	1722	19400	200000
ρ (kN/m^3)	24,72	22,40	25	78,50
f_c (MPa)	9,18	3,50	15	---
f_t (MPa)	1,22	0,06	2,71	---
f_y (MPa)	---	---	---	500

In order to apply the equivalent frame modeling (EFM) approach, masonry must be modelled as a homogenized material. Yardim et al. [14] address this issue by using the formulas cited in Eurocode 6 [15], which are in agreement with the results of the experimental tests they carried out as part of their study. These formulas allow the calculation of the strength (f_k), Young's modulus (E) and Coulomb modulus (G) according to the following equations:

$$f_k = k f_b^{\alpha} f_j^{\beta} \tag{1}$$

$$E = 500\, f_k \tag{2}$$

$$G = 0.4E \tag{3}$$

where f_k is the strength of the masonry, and f_b and f_j represent that of the rubble and mortar respectively, while the coefficients α , β and k are taken equal to 0.70 , 0.39 and 0.55 , respectively [14, 16].

The final mechanical properties used in the modeling, determined using previous equations are summarized in Table 2.

Table 2 : Mechanical characteristics of the masonry

	Masonry
E (MPa)	2327,6
f_c (MPa)	4,23
f_t (MPa)	0,22
G (MPa)	931

MACRO-MODELING APPROCH IN OPENSEES AND STKO

The non-linear analysis in this study were carried out using STKO program [17]. STKO, The Scientific ToolKit for OpenSees, is an advanced Graphical User Interface (GUI) for OpenSees, an open access computer platform, specific to earthquake engineering research [17]. Although a very powerful computational tool, OpenSees requires the development of a programming algorithm and does not allow the visualization of either the input data or the results. STKO facilitates its use by offering an advanced graphical toolkit to OpenSees users, who can customize and program processors according to their needs.

Equivalent Frame modeling of masonry structures

Since many traditional buildings are located in high seismicity regions, there is a growing interest in developing simple and efficient models to predict the behavior of masonry structures [18]. Thus, in parallel to the complex finite element modeling (FEM) approaches, simplified ones have been proposed, namely the equivalent frame modeling (EFM) methodology. In this approach, the structure is discretized into one-dimensional macro-elements forming a frame: vertical elements (piers), horizontal elements (spandrels) and rigid zones that provide the connection between the two.

The crucial step in the modelling process is the determination of the effective length of the "piers", which represent the main resistant components of the wall [19]. Using the two most commonly adopted discretization criteria, namely Dolce and Augenti, Siano et al. [20] concluded that greater accuracy characterizes the Dolce model in predicting the overall strength of the masonry structure, while the Augenti model shows better performance in predicting failure modes. In the present study, Augenti approach has been used to describe the geometry of the macro-elements (Fig. 3).

To represent the nonlinear behavior of piers and spandrels, the force-based approach (FBA) has been adopted [21]. The flexural behavior is modeled by the fiber discretization. The shear behavior is considered by introducing nonlinear springs.

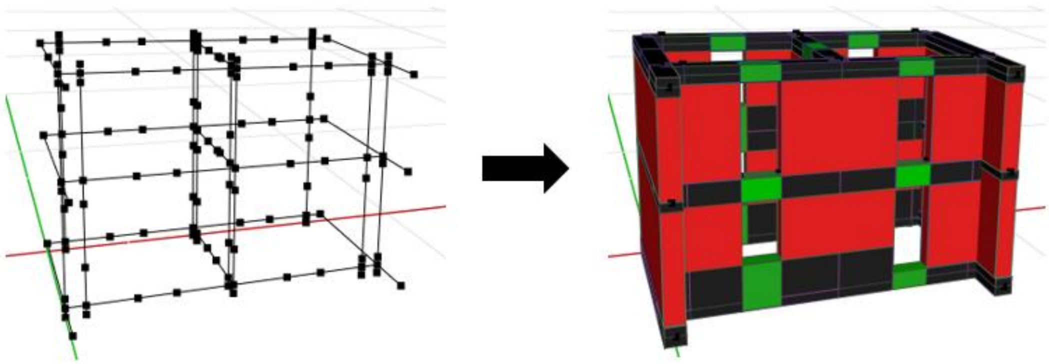


Fig. 3 : Discretization of the building into equivalent frames following the Augenti approach.

Constitutive laws

In the equivalent frame modeling (EFM), the masonry structure is modeled by a set of one-dimensional elements to which appropriate laws are assigned. These laws describe the bending and shear behavior of the "spandrels" and "piers" respectively.

To simulate the masonry fiber uniaxial behavior, the Orakcal et al. [22] law was used as it considers the material tensile strength, and therefore offers a more accurate description of the bending behavior. Regarding the shear one, Lowes et al. [23] law has been used for piers and Camata et al. [24] law was adopted for spandrels.

Horizontal reinforcements

Since the explicit introduction of the horizontal bands in the analytical model is not possible in the equivalent frame modeling technique, the literature proposes an equivalent way to take into account the reinforcement of the macro-elements crossed by the bands, by adjusting their behavior laws. Gattesco et al. [13] note that these strips act as connecting beams, providing more stiffness and strength to the structure. This was further confirmed by the results of their experimental analysis, which showed that the implementation of horizontal bands prevented the overturning of the piers, permitting a gradual loss if spandrels' resistance thereby preventing a sudden collapse. Thus, referring to the NTC [25], and backed by their experimental results, the Gattesco et al. provide alternative formulas to calculate the ultimate strength of the macro-elements in this case.

RESULTS

Two structural models were developed, one with and one without reinforcement bands. Both models were subjected to nonlinear static pushover analysis, done in two phases: the first involves the application of vertical loads that are mainly gravity loads (in force control), while the second one consists in the application of horizontal loads (in displacement control), until the failure conditions are reached. At each iteration, equilibrium is guaranteed by verifying the Newton-Raphson criteria, and convergence is assured with a residual tolerance of 1×10^{-5}.

Three points were then chosen for the application of horizontal loads in agreement with the SmartNet teams to capture the maximum resistance and displacement achieved in both directions x and y (see Fig. 4). A triangular distribution of forces proportional to the height of the building was employed, whose shape follows the deformation compatible with the first vibration mode. The corresponding force-displacement curves obtained using STKO are shown in Fig. 5.

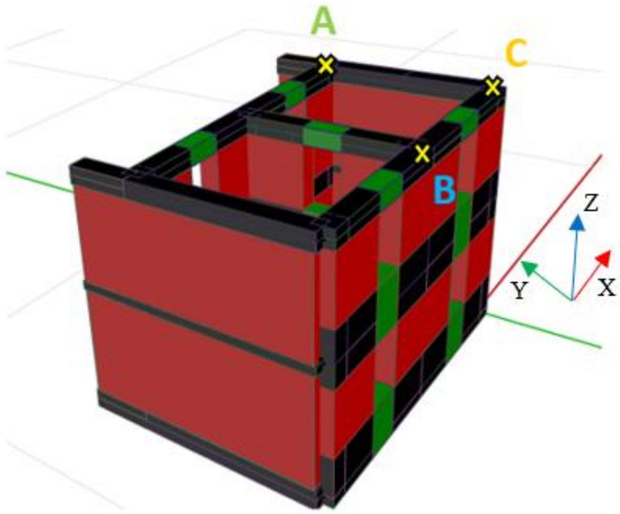


Fig. 4: 3D Model of SSF template. Points A, B and C are those used as control points in the pushover analysis.

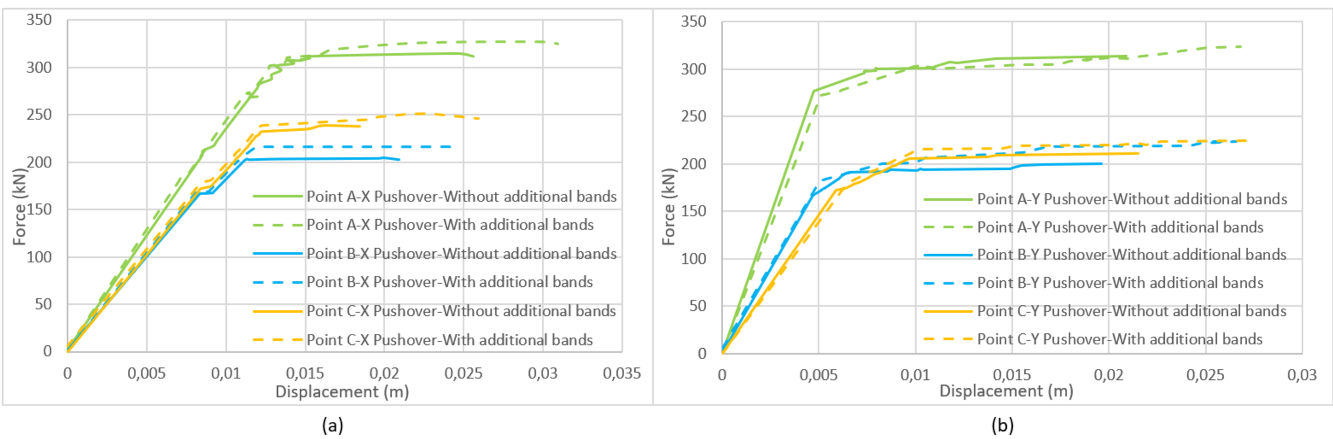
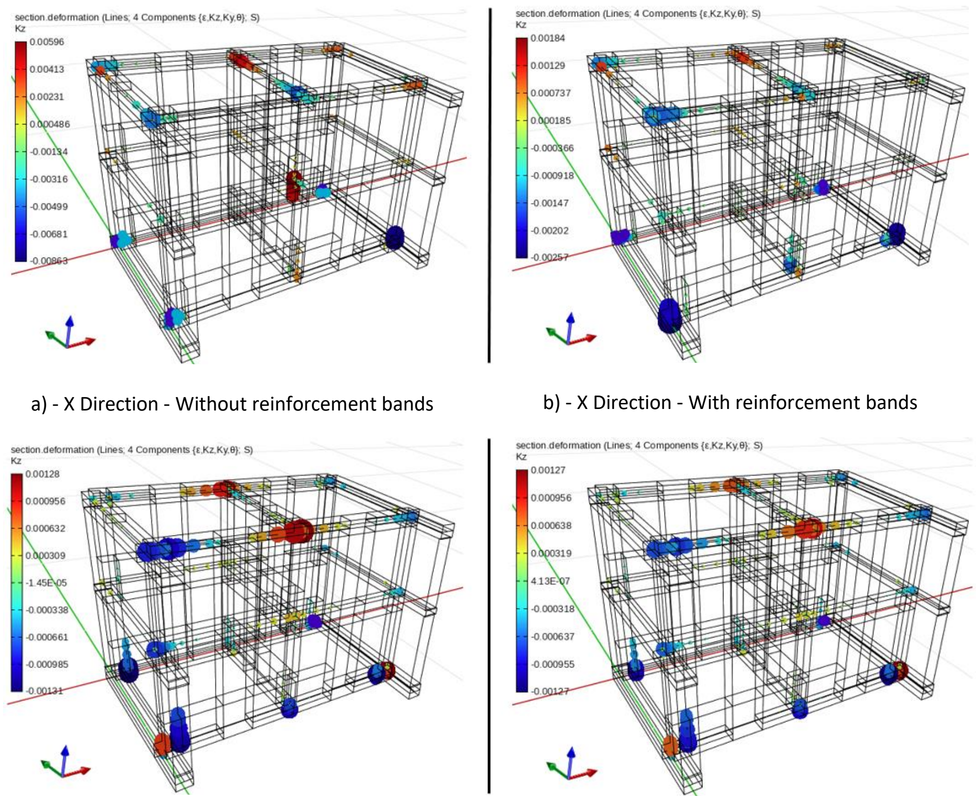


Fig. 5 : Pushover curve of the SSF template with RC bands in (a) X direction and (b) Y direction captures at three control points A, B, C

It is found that the failure of a given macro-element corresponds to the first mechanism reached during the seismic loading: shear sliding, diagonal cracking, or rocking. The sequence of the plastic hinges formation is illustrated in Fig. 6, as a function of the plastic curvature (kz). The plastic hinges are formed first in the piers and then in the spandrels. In terms of comparison between the two configurations, smaller curvatures are obtained when adding the reinforcement bands along the X and Y directions.



a) - X Direction - Without reinforcement bands

b) - X Direction - With reinforcement bands

c) - Y Direction - Without reinforcement bands

d) - Y Direction - With reinforcement bands

Fig. 6 : Sequence of plastic hinges formation according to the two configurations: (a) with and (b) without additional bands

Table 3 : Results of the Pushover Analysis in the Configuration without Additional Bands

	Without additional bands											
	A				**B**				**C**			
	V_u (kN)	D_e (mm)	D_{max} (mm)	μ	V_u (kN)	D_e (mm)	D_{max} (mm)	μ	V_u (kN)	D_e (mm)	D_{max} (mm)	μ
Direction X	311,63	8,61	25,6	2,97	202,88	8,29	20,93	2,52	247,19	17,01	35,67	2,10
Direction Y	313,64	4,75	20,91	4,40	202,89	4,87	19,71	4,05	121,12	5,2	26,64	5,12

Table 4 : Results of the Pushover Analysis in the Configuration with Additional Bands

	With additional bands											
	A				**B**				**C**			
	V_u (kN)	D_e (mm)	D_{max} (mm)	μ	V_u (kN)	D_e (mm)	D_{max} (mm)	μ	V_u (kN)	D_e (mm)	D_{max} (mm)	μ
Direction X	324,42	7,03	30,92	4,40	213,93	8,04	24,67	3,07	245,74	8,29	25,91	3,13
Direction Y	327,27	5,10	26,80	5,25	223,53	5,05	25,32	5,01	224,85	5,64	27,11	4,81

Table 3 and

Table 4 summarize the results obtained for the base shear (V_u), yield and maximal displacements (D_e and D_{max}) and displacement ductility ($\mu = D_{max}/D_e$) . It can be seen that the introduction of the horizontal bands in the building design does not have a significant effect on the base shear (V_u) but plays an important role in increasing the ductility of the structure (μ): only 10 percent of the increase in base shear strength was recorded while the ductility increases by 48 percent.

The same conclusion was reached by the University of Bristol team [26]. Their modeling was based on microelement discretization approach (DEM) while the analysis was carried out by STKO/OpenSees. Their results showed 5 percent increase in strength, and 45 percent for ductility. Being more reliable but complex to apply in a developing context, their study supports the fact that the reinforcement proposed by SSF can effectively increase the ductility capacity without significantly affecting the base shear value.

CONCLUSIONS

In this study, the analysis of a reinforcement approach for masonry structures was performed. The overall aim of this research was to characterize the seismic response of a two-story building, provided by SSF. In the preliminary phase, the comparison was made using the results of the static pushover. The analysis concluded that the proposed reinforcement configuration increases the ductility of the structure but does not significantly increase the peak shear at the base. These observations were validated by another study, carried out by the University of Bristol partners, that conducted the analysis with a more complex and sophisticated modelling methodology. The similarity of the initial results showed that equivalent-frame modelling has potential to estimate seismic response of these type of structures.

Drawing inspiration from traditional constructions to design more seismically efficient structures, without ruining the basic architectural appearance and structural behavior, is a possible solution to the problem of building collapse in developing countries. More general conclusions on the improvement of the seismic response of the case study building following the introduction of the horizontal reinforcement strips necessitate further analysis and the comparison with a SmartNet team that focused on the time history analysis. Due to the lack of current availability of these results, as the respective models are under development, the conclusions reported herein are preliminary and limited only to the strength and ductility capacity.

ACKNOWLEDGMENTS

The financial support of the Natural Sciences and Engineering Research Council of Canada (NSERC) is gratefully acknowledged.The authors would also like to thank Smart Shelter Foundation (SSF) and SmartNet (Seismic Methodologies for Applied Research and Testing of Non-Engineered Techniques), for providing the design of the case study building and the typical material properties used in Nepal, as well as Prof. Flavia di Luca and her team from University of Bristol for valuable discussions.

REFERENCES

[1] Arya, A.S., *Non-engineered construction in developing countries - an approach toward earthquake risk prediction.* Bulletin of the New Zealand National Society for Earthquake Engineering, 2000. **33**(3): p. 187-208.
[2] Sinha, R., S. Brzev, and G. Kharel, *Indigenous earthquake-resistant technologies-An overviw.* 13th World Conference on Earthquake Engineering, 2004.
[3] 2023 Turkey–Syria earthquake.
[4] Audefroy, J.F., *Haiti: post-earthquake lessons learned from traditional construction.* Environment and Urbanization, 2011. **23**(2): p. 447-462.
[5] Booth, E., *Dealing with earthquakes: the practice of seismic engineering 'as if people mattered'.* Bulletin of Earthquake Engineering, 2018. **16**(4): p. 1661-1724.
[6] Charleson, A., A. Nonoguchi, and A. Maeshima, *Towards resilient non-engineered construction.* UNESCO, 2016.
[7] Ortea, J., G. Vasconcelos, and M. Correia, *An overview of seismic strenghtening techniques traditionally applied in vernacular architecture.* 9th International Masonry Conference, 2014.
[8] *Smart Shelter Foundation.* 2005.
[9] Schildkamp, Silvestri, and Araki, *Rubble Stone Masonry Buildings with Cement Mortar: Base Shear Seismic Demand Comparison for Selected Countries Worldwide.* Frontiers in Built Environment, 2021. **7**.
[10] Schildkamp, M. and Y. Araki, *School Buildings in Rubble Stone Masonry With Cement Mortar in Seismic Areas: Literature Review of Seismic Codes, Technical Norms and Practical Manuals.* Frontiers in Built Environment, 2019.
[11] Parajuli, R.R., A. Furukawa, and D. Gautam, *Experimental characterization of monumental brick masonry in Nepal.* Structures, 2020. **28**: p. 1314-1321.

[12] Bothara, J., et al., *Experimental seismic testing of semi- reinforced stone masonry building in mud mortar.* 2019 Pacific conference on earthquake engineering and annual NZSEE conference, 2019.
[13] Gattesco, N., L. Macorini, and A. Dudine, *Experimental Response of Brick-Masonry Spandrels under In-Plane Cyclic Loading.* Journal of Structural Engineering, 2016. **142**(2).
[14] Yardim, Y., E. Mustafaraj, and E. Luga, *Effects of Material Properties on Seismic Vulnerability Assessment of Unreinforced Masonry Buildings.* KSCE Journal of Civil Engineering, 2020. **24**(5): p. 1557-1567.
[15] Eurocode 6, *Design of masonry structures.* 2004.
[16] FEMA 356, *Pre-standard and commentary for the seismic rehabilitation of buildings.* 2000.
[17] Parisse, F., et al., *Benchmarking the seismic assessment of unreinforced masonry buildings from a blind prediction test.* Structures, 2021. **31**: p. 982-1005.
[18] Matteo, P., S. Enrico, and C. Guido, *Nonlinear analysis of masonry structures using fiber-section line elements.* Earthquake Engineering & Structural Dynamics, 2019. **48**(12): p. 1345-1364.
[19] Quagliarini, E., G. Maracchini, and F. Clementi, *Uses and limits of the Equivalent Frame Model on existing unreinforced masonry buildings for assessing their seismic risk: A review.* Journal of Building Engineering, 2017. **10**: p. 166-182.
[20] Siano, R., et al., *Numerical investigation of non-linear equivalent-frame models for regular masonry walls.* Engineering Structures, 2018. **173**: p. 512-529.
[21] Raka, E., et al., *Advanced frame element for seismic analysis of masonry structures: model formulation and validation.* Earthquake Engineering & Structural Dynamics, 2015. **44**(14): p. 2489-2506.
[22] Orakcal, K., L. Massone, and J. Wallace, *Analytical modeling of reinforced concrete walls for predicting flexural and coupled shear-flexural responses.* Pacific Earthquake Engineering Research Center (PEER), 2006.
[23] Lowes, L.N., N. Mitra, and A. Altoontash, *A beam-column joint model for simulating the earthquake response of reinforcednconcrete frames.* PEER Report 2003/10 Pacific Earthquake Engineering Research Center College of Engineering University of California, 2004.
[24] Camata, G., et al., *Validation of non-linear equivalent-frame models for irregular masonry walls.* Engineering Structures, 2022. **253**.
[25] NTC, *Italian Code for Structural Design.* Official Bullettin No. 29, 2008.
[26] Syrett, L., et al., *Comparison of pushover curves of a two-storey stone cement masonry building with and without additional concrete bands.* 3rd European conference on earthquake engineering and seismology, 2022.