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Earthquake Resistant Non-Engineered Construction in Developing Countries Utilizing Appropriate Technology

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ABSTRACT

Appropriate technology according to Wikipedia is: a movement (and its manifestations) encompassing technological choice and application that is small-scale, affordable by locals, decentralized, labor-intensive, energy-efficient, environmentally sound, and locally autonomous.

This paper deals with utilizing appropriate technology based on the latest technological advancements to make non-engineered people's housing earthquake resistant in developing countries. The authors provide two examples for the purpose: first, constructing as well as strengthening of existing vulnerable houses in Indonesia. The second example is how to make mud mortar stone masonry houses in Nepal earthquake resistant.

Key words: appropriate technology, non-engineered houses in developing countries

NON-ENGINEERED CONSTRUCTIONS IN INDONESIA

In Indonesia on the average every two years, there is a disastrous earthquake that caused many non-engineered constructions (mostly common people's houses and one-story school buildings) collapsed and killed people (Figure 1). This is a clear indication that those non-engineered construction are not earthquake resistant.

Bali – 1976

Flores – 1992

West Sumatra – 2009

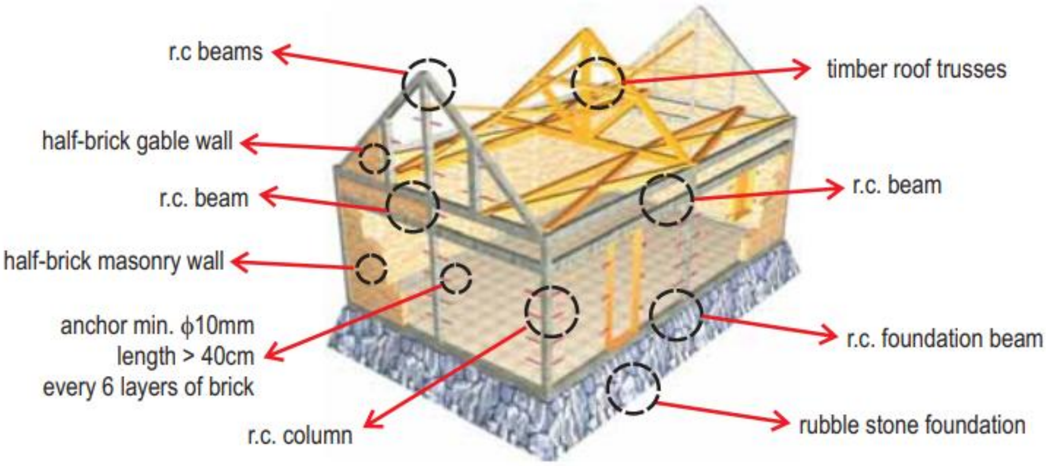
Pidie Jaya – 2016


Lombok – 2018


Palu – 2018

Fig. 1 Damage of non-engineered constructions in Indonesia [1]

The prevailing type of Indonesian people's houses are brick or concrete block masonry construction, most of them used reinforcement, the so called "practical columns and practical beams" as confinement (Figure 2). Theoretically, such type of masonry house is earthquake resistant if appropriately constructed, meaning that the quality of materials and the workmanship of brick laying and assembling the practical columns and beams are correctly done. Unfortunately, the local artisan's skill in brick laying and assembling the joints of the practical columns and beams reinforcement are deteriorating, thus resulting in poorly built houses that can be heavily damaged or collapsed when shaken by earthquakes.



Note: All building components (foundation, columns, beams, walls, roof trusses, roofing) must be tied to each other, so that when shaken by earthquakes, the building will act as one integral unit.

Fig. 2 Earthquake resistant masonry house using practical columns and practical beams [1]

In general, the damage and collapse of those non-engineered reinforced masonry houses during earthquakes are mostly caused by the poor quality of materials (Figure 3) and poor workmanship, resulting in, among others insufficient or improper foundation (Figure 4), poor detailing (Figure 5), poor mortar quality, poor concrete quality (Figure 6), and poor brick-laying (Figure 7). Besides that, it is a common practice that roof trusses are not strongly anchored to the ring beams. The reinforcement of the practical columns and beams are mostly not in accordance with the requirements. The reinforcing bars detailing are also not appropriately done for earthquake resistance. Therefore, the houses are constructed based on wrong prevailing practice.


Poor quality of bricks (left);
Gradation of sand used for concrete mixture does not meet standards (right)

Fig. 3 Poor quality of materials resulting damage and collapse of non-engineered reinforced masonry houses [1]

Fig. 4 Improper stone foundation [1]

Fig. 5 Poor detailing of reinforcing bars [1]

Fig. 6 Poor concrete quality [1]

Fig. 7 Poor brick laying [1]

HOW TO REDUCE THE DEFICIENCIES DUE TO THE SHORTCOMINGS MENTIONED ABOVE

To reduce the deficiencies caused by inappropriate practice, local artisans and officials should be educated and/or trained with regards how to mix concrete / mortar properly; how to lay bricks in accordance with established rules; how to correctly bend reinforcing bars for practical columns and beams, particularly assembling reinforcing joints of beams & columns, beams-beams correctly to make it earthquake resistant; also educate local artisans and officials that all building materials used for construction shall comply with the existing regulations.

Currently, there are approximately 65 million of people's houses scattered all over Indonesia that are threats to the inhabitants when shaken by earthquakes. In Indonesia there are approximately 83,931 villages all over Indonesia from the eastern to the western part (equal distance from California to New York) [2]. Apart from that, Indonesia consists of 17,504 islands and therefore the options to educate and train artisans as well as officials will take a very long time before we can see the results. In the meantime, destructive earthquakes occur on the average every 2 years and could be anywhere in Indonesia. Therefore, we cannot waste time by waiting the results of training local artisans and officials to make an impact. Having said the above, it is very urgent for Indonesia to introduce an innovative method constructing earthquake resistant masonry houses, bypassing the shortcomings of brick laying, assembling ductile reinforcement, and the use of poor-quality materials.

The total amount of non-engineered people's housing in Indonesia is approximately 30,218,454 in urban area and 30,887,004 in rural area [3]. Hence, 85% are located in strong earthquake areas (Figure 8). Therefore, all new buildings must be constructed earthquake resistant based on the new method and all existing non-engineered people's housing which were built based on the old incorrect practice, namely the so called brick masonry / concrete block masonry confined with practical columns and practical beams, shall be retrofitted with a simple, practical, affordable, and replicable method. For such purpose, it is advisable to apply "appropriate technology" for constructing the new non-engineered houses as well as retrofitting the existing non-engineered houses / one-story school buildings.

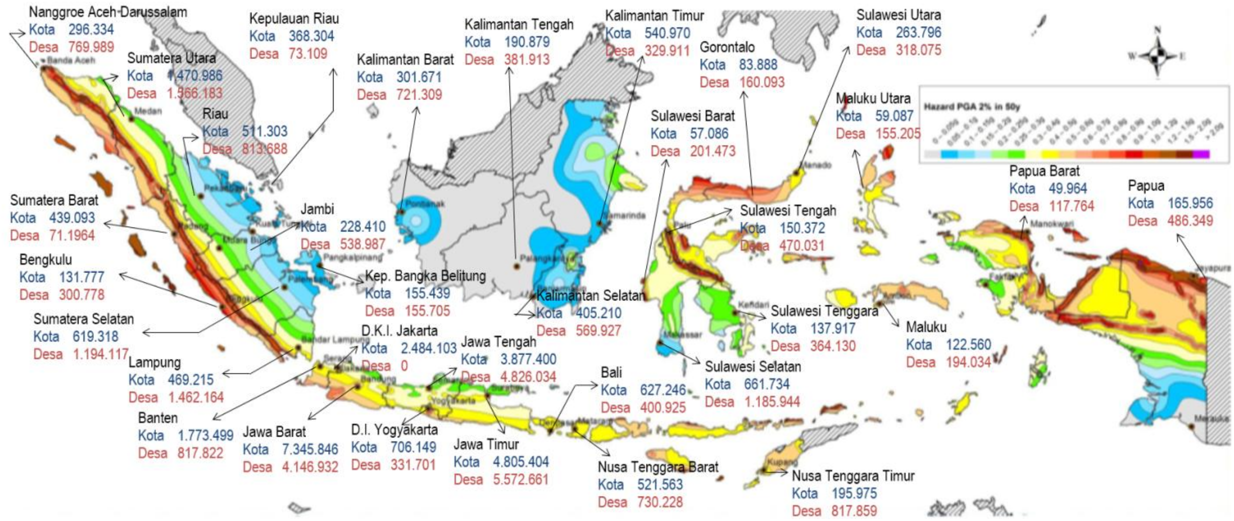


Fig. 8 Number of non-engineered people's housing in Indonesia; ±85% located in strong earthquake areas

In 1980, the first author and Professor Arya when writing the IAEE monograph for non-engineered construction, did suggest that masonry walls of people's housing be wrapped with wire mesh on both sides of the walls [4]. However, at that time the suggestion was not accompanied by analysis.

In later years, the above idea, wrapping of walls with wire mesh was further developed by the first author and use the term ferrocement layers. Ferrocement is a thin composite consisting of cement mortar matrix reinforced with small diameter wire mesh encapsulated in the matrix [5, 6]. The thickness of ferrocement is approximately 10-50 mm and uses rich cement mortar; no coarse aggregate is used; and the reinforcement consists of one or more layers of continuous / small diameter steel wire / weld mesh netting. Ferrocement was invented and patented by a French engineer Joseph-Louis Lambot in 1852. Nowadays, ferrocement is also termed as fabric cement if wire fabric mesh is used as reinforcement.

Ferrocement layers are very useful for strengthening unreinforced masonry walls since wrapping with ferrocement layers on both side of the walls, substantially improve the shear strength, in-plane strength, out-of-plane strength, and ductility [7]. Some proposed strengthening of wall corners only using ferrocement [8]. Retrofitting unreinforced masonry walls using ferrocement is a common technique, but there are no design guidelines for the purpose [9]. No reliable mathematical or computational tool is accessible in the open literature to estimate the effect of such a retrofitting technique quantitatively because of the lack of experimental and analytical information with regards to this method.Therefore, in the past, the retrofitting procedures with ferrocement layers are being done based on empirical judgments [9, 10].

In 2010, the first author introduced an analysis of unreinforced masonry wall wrapped with ferrocement layers on both side of the wall using the analogy of sandwich structures. The result is good enough to prove that ferrocement layers are suitable for earthquake resistance. The analysis was published in the book "Learning from Earthquakes Damage: Non-Engineered Construction in Indonesia" [1].

In 2001, the first author did introduce strengthening an office building in Bengkulu, Indonesia, using ferrocement layers on both side of the wall. Such retrofitting method using ferrocement as strengthening layers was also used when retrofitting two school buildings in Bandung, i.e. In 2006 SDN Cirateun Kulon II and in 2007 SDN Padasuka II Soreang [11]. Subsequently the method lining existing masonry houses as well as one-story school buildings with ferrocement layers was applied in West Sumatra, 2009.In 2009, the first author did strengthen many damaged people's houses as well as school buildings and engineered constructions using ferrocement layers and provided the analysis (Figure 9).

SDN Padasuka II Soreang

SDN 13 Batu Gadang, Padang

Retrofitting house at Balai Baru

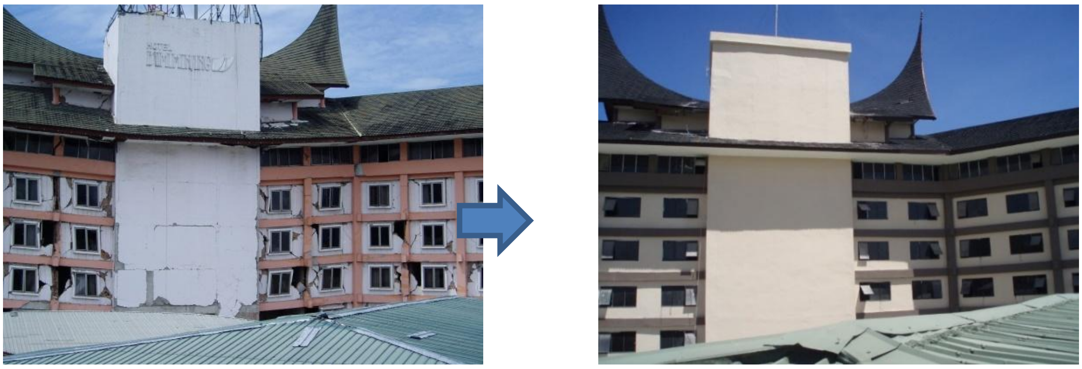
Retrofitting a heritage church, Kapel St. Leo, Padang

Retrofitting a heritage church, Kapel St. Leo, Padang

Retrofitting a heritage church, Kapel St. Leo, Padang

BumiMinang Hotel, Padang

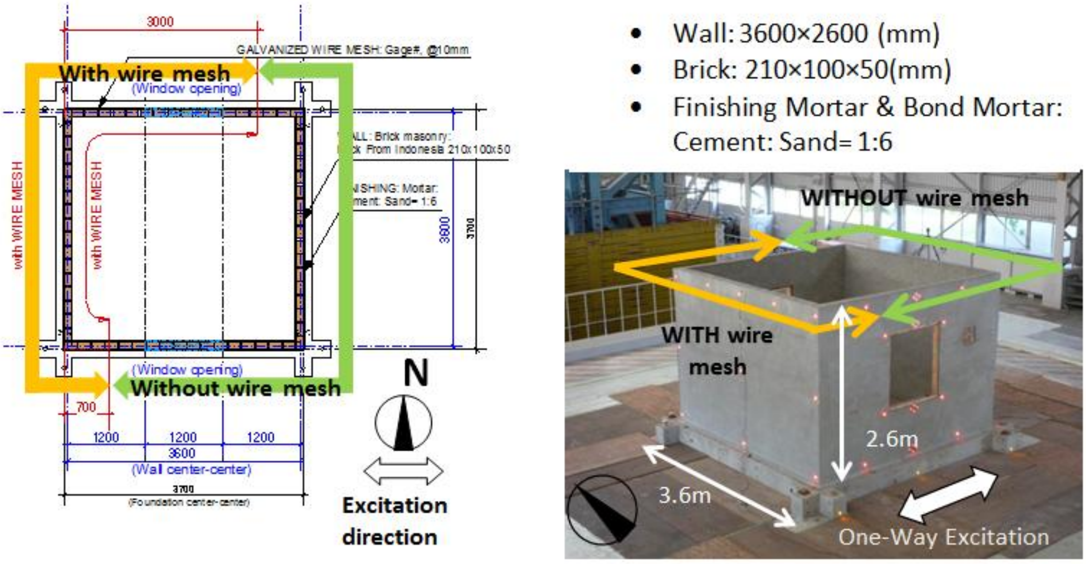
BumiMinang Hotel, Padang



BumiMinang Hotel, Padang

Fig. 9 Example of retrofitting buildings using ferrocement as strengthening layers

Following the good results of the analysis and actual implementation for many buildings in West Sumatra, in 2012 NIED (National research Institute for Earth science and Disaster prevention) and Mie University conducted a shaking table test in Tsukuba [12, 13] (See Figure 10). Half of the building (East wall and main part of the South wall) were only plastered and not reinforced using wire mesh, while the rest (West wall and main part of the North wall) were reinforced using wire mesh as ferrocement layers. The record used was JMA Kobe 100% (0.89g).



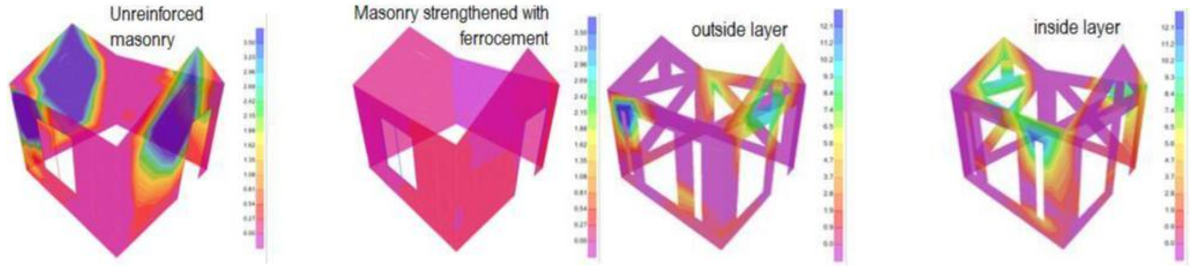
Outline of model structure for the shaking table experiment of reinforced walls using wire mesh

Sequence pictures of the collapsed of unreinforced masonry walls

Fig. 10 Shaking table test of masonry building strengthened using ferrocement overlay, 2012

After the successful test, the first author suggested not to **wrap** the wall with ferrocement layers but to bandage only. In 1980, strengthening by **bandaging** masonry walls with ferrocement layers was already introduced in the Guidelines for Earthquake Resistant Non-Engineered Construction [4]. For the purpose, the first author did the analysis for the strengthening of masonry walls by bandaging using the sandwich analogy and the results were good enough.

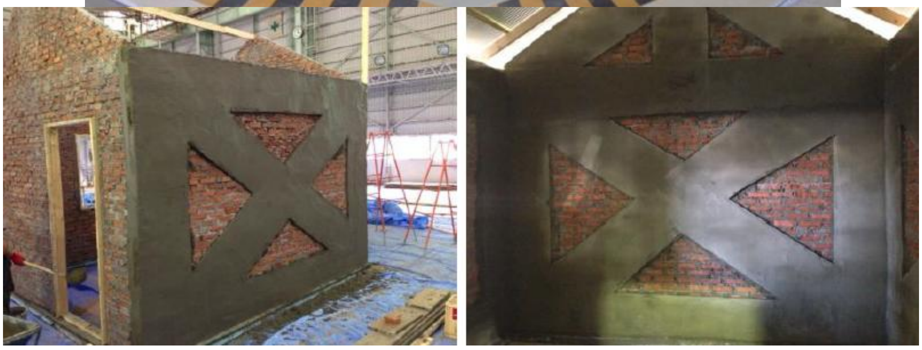
In 2014, NIED and the second author invited the first author to do a full-scale shaking table test in Tsukuba for masonry buildings **bandaged** with ferrocement layers. There were two model structures built on the shaking table in NIED, Tsukuba. Both models were of the same size and built as unreinforced masonry building (without RC confinement columns and beams). The first model (Model A) the original unreinforced masonry structure without plaster, and the second (Model B) the same masonry structure strengthened by providing bandaging using ferrocement layers on both sides of the walls, acting as sandwich structures. The analysis was explained prior to the testing. The test results were very successful and matched with the analysis performed (Figure 11 and Figure 12). The report of the shaking table test was published in the Journal of Disaster Research [14].



at brick-wall at brick-wall at ferrocement at ferrocement

Tensile stresses pattern due to JMA Kobe 100% at 16.16s (blue color meaning the stress exceeded the allowable stress)

Fig. 11 Analysis results of the masonry building strengthened by providing bandaging using ferrocement layers [1]



Completed ferrocement layers

Gable wall Model A collapsed due to 100% JMA Kobe; Model B survived

2g JMA Kobe input motion: Model A collapsed and Model B still standing

Fig. 12 Shaking table test of the masonry building strengthened by providing bandaging using ferrocement layers, 2014 [1, 14]

The use of ferrocement for strengthening masonry walls is categorized as “appropriate technology”. Meaning of appropriate technology is a method, simple to use, affordable, replicable, using local material and local masons.To overcome the shortcomings mentioned previously in constructing Indonesian masonry houses (Figure 2), the first author introduces a new method of constructing people’s housing, using ferrocement bandaging and abandoning the use of the so-called practical columns and practical beams (Figure 13). The first author also purposesto replace the rubble stone foundation with an inverted RC T-beam (Figure 14). This is to make the construction of people’s houses much simpler and stronger. The advantages of constructing masonry houses bandaged using ferrocement layers are:

- Feasible in the context of social, cultural, economical, political& technical constraints typical in development countries.
- Using local materials, local tools, and local tradesmen’s skills.
- The cost will be lower compared to the cost of constructing "traditional" masonry houses using practical columns and practical beams.
- The construction period is faster and simpler compared to constructing of the “traditional” masonry houses.
- The methodology can be carried out by homeowners with minimal financial and technical assistance, and do not require extensive reconstruction or modification of the existing buildings.

Fig. 13 Masonry houses using ferrocement bandaging (Palu, 2020)

Fig. 14 Inverted RC T-beam (Palu, 2020)

MUD MORTAR STONE MASONRY HOUSES IN NEPAL

During the April 25, 2015 Nepal earthquake, approximately 262,600 buildings were damaged, and 489,500 buildings collapsed [15]. Unfortunately, most of the buildings in themountainous regions of the Himalaya in Nepalthat collapsedwere non-engineered buildings, i.e. mud mortar stone/brick masonry houses (Figure 15).

Fig. 15 Mud mortar stone masonry houses collapsed due to April 25, 2015 earthquake [16]

The common people's houses in the mountainous areas of the Himalaya is mud mortar stone masonry. This is because stone and mud are abundant and practically free, hence since ancient times people are familiar with constructing mud mortar stone masonry houses. Unfortunately, mud has practically no strength in tension as well as shear and stone are relatively heavy, and the climate is very dry. Therefore, the mud becomes dry most of the time (becomes wet again when there is rain) and the stone masonry is practically not bonded.

The first author was invited by JICA to try to find a solution for those mud mortar stone masonry houses that are not earthquake resistant and killed many people. In November 2015 and March 2016, the first author, together with the second author as a JICA expert at that time, went to Nepal and toured the mountainous region to survey and assist Nepal after the 2015 April earthquake. The purpose of the visits was to find solutions that is simple, affordable, replicable, and suiting the local culture to make such mud mortar stone masonry houses earthquake resistant.

After surveying for 3 days along the Himalayan mountainous regions, the first and second authors observed that along the mountainous routes, many slope embankments were protected by gabions and none of them were damaged during the 2015 April earthquake (Figure 16). The first and second authors also found that in the mountainous regions the use of gabions is common and there are even "several big storages of gabion wires". The use of gabions in the Himalayan regions can be categorized as using appropriate technology because stone is free, gabion wires net are easy to get and people are very familiar on how to construct gabions.

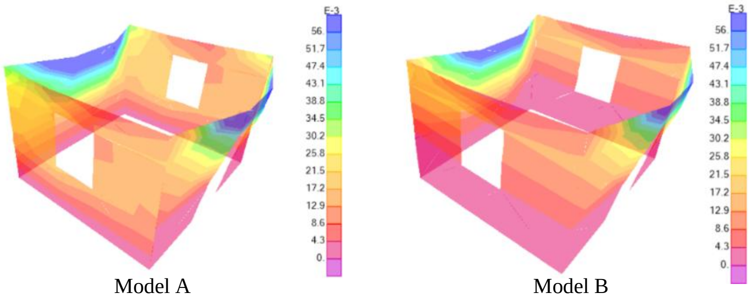
Having observed the above, the first and second authors thought that it will be good to introduce constructing the mud mortar stone masonry walls with gabion "bricks of 210x100x60mm" and stack them as "brick walls". Such model has been analyzed by the first author and the results were very promising since it can withstand strong earthquake shaking. However, if this is introduced to the local people, their expertise in building mud mortar stone masonry walls without any reinforcement might be compromised, meaning that they must learn a new trade, building houses with gabion "bricks" walls. Besides that the existing houses must be reconstructed from zero if the method of "gabion bricks" is adopted. Therefore, this method was abandoned, instead the first and second authors thought it might be better to wrap the existing mud mortar stone masonry houses with gabion wires from the inside as well as outside of the walls and both wires are "stitched" with 2-mm gabion wires with a distance of 30cm.

Fig. 16 Gabion is used as retaining walls [16]

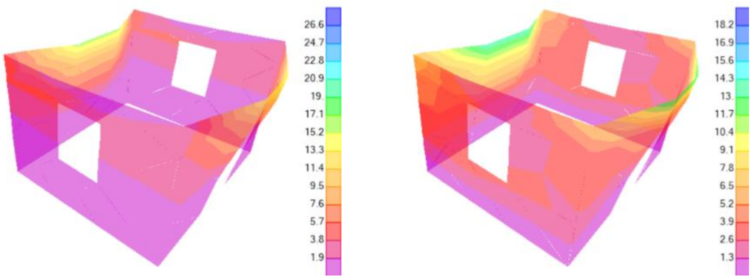
The proposed method was analyzed by the first author and the analysis results show that during a strong earthquake, the wrapped mud mortar stone masonry walls will be deformed substantially but do not collapse (Figure 17). On February 26, 2019 and June 4, 2019, a full scale shaking table tests for mud mortar stone masonry houses were conducted in Tsukuba by NIED in cooperation with the second author and the association of gabion manufacturers of Japan. The shaking table tests demonstrated that the strengthening using gabion wire mesh, is effective in preventing collapse of mud mortar stone masonry walls when shaken by earthquakes (Figure 18). This shaking table test was published in Journal of Scientific and Engineering Research [16]. Therefore, the ”traditional” practice to build mud mortar stone masonry houses strengthened by wrapping with 2 mm gabion wire mesh can save human lives. Wrapping gabion wire mesh to existing houses can be done without too much disturbance, therefore, it is suitable for strengthening all the existing mud mortar stone masonry houses in Nepal.

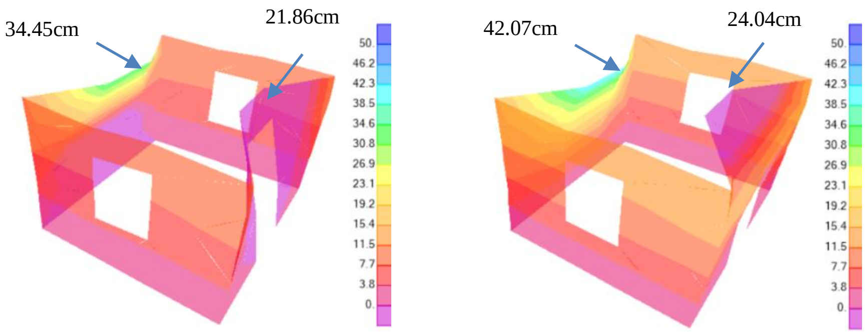
The method introduced can be applied for existing houses as well as new houses and it is easy, simple, affordable, replicable, and suiting the local culture and do not change people’s tradition to build mud mortar stone masonry houses. Thus, it is in accordance with the requirements of appropriate technology.

Maximum tensile stress pattern in stone walls due to 50% JMA Kobe; the stresses at some part of walls were exceeded (in blue colors), walls can be damaged or collapsed.



Maximum tensile stress pattern in gabion wire mesh for Model B due to 50% JMA Kobe; maximum stress 27MPa was smaller than the allowable stress (435MPa).





Due to 70% JMA Kobe   Due to 100% JMA Kobe

Maximum deformation pattern of Model B.

Fig. 17 Analysis results of unreinforced mud mortar stone masonry walls: without plaster (Model A); with strengthened by wrapping 2mmgabion wire mesh on both sides of the walls (Model B) [16]

Model A – Non-Retrofitted unreinforced mud mortar stone masonry without plaster (left);
Model B – Retrofitted unreinforced mud mortar stone masonry strengthened by wrapping 2mm gabion wire mesh on both sides of the walls (right)

Construction of mud mortar stone masonry houses wrapped with gabion wire mesh

Model B, mud mortar stone masonry strengthened by wrapping 2mm commercial type gabion wire mesh on both sides of the walls, constructed at the end of May 2019


Model A: West and East walls collapsed due to out-of-plane loading; large cracks from window openings in North and South walls (left); Model B: Deform but did not collapse (right)


The first and second authors – Model A collapsed and Model B still standing due to 70% JMA Kobe

West Wall

East Wall

June 4, 2019 shaking table test with 100% JMA Kobe input motion for Model B only: substantial cracking and deformations but did not collapse.

Fig. 18 Full shaking table test of mud mortar stone masonry houses [16]

CONCLUSION

From the above 2 examples, it is hoped that all developing countries can find solutions for their earthquake resistant people's housing based on "appropriate technology", utilizing the latest technological advancements, thus not introducing strengthening using FRP, epoxy, etc. which are alien for common people all over the world.

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