Behaviour of interlocking block structures under dynamic loading: A review

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***Abstract*: Earthquake imposes serious harm to non-designed structures in countryside regions of the world. Many affordable yet safe housing strategies for individuals of such regions are being proposed by many researchers. In this regard, interlocking block structure is one of the potential solutions presented by these researchers. The aim of this paper is to review the behaviour of interlocking block prototype structures under dynamic loading based on previous researches. Behaviour of these prototype interlocking structures were investigated by various researchers using low to large scale shake table in the laboratory. Their mechanism of dynamic loading, from real life earthquake phenomena to simplified apparatus in the form of shake table done on prototypes and on real scale, is presented. A brief overview of the parameters evaluated in these studies is also discussed. The viability of different interlocking patterns in increasing the dynamic properties are featured and conclusions drawn are gathered to have a superior understanding of the adequacy of these interlocking patterns against dynamic loading. The output of these methodologies based on empirical relations to predict the actual behaviour of interlocking block structures for real life application are reported. Few limitations to bridge the gap between prototype testing and real-life scenarios are identified and their analytical solutions is recommended.**

***Keywords*: Dynamic loading, Interlocking block structures, Prototype testing, Shake table.**

I. INTRODUCTION

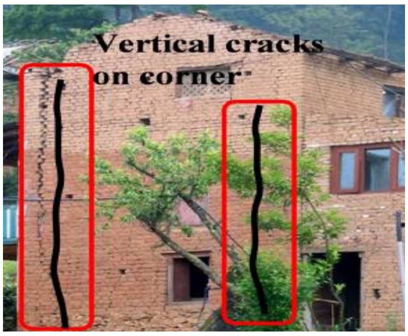
Earthquake is one of the dangerous and life-threatening natural disaster. Earthquakes produce different damaging impacts to the zones they act on. This incorporates harm to structures and in worst scenarios the loss of human life. The impacts of the vibrations generated by earthquakes normally prompts the destruction of civil engineering structures such as buildings, bridges, and dams etc. Specifically, masonry buildings in seismic zones of rural and urban regions throughout the world constitutes a hazard to human life. Because strong ground motions generated by earthquake badly damage the masonry structures. The Kashmir earthquake of October, 2005 caused more than 86,000 causalities, more than 80,000 human injuries and an estimated total economic loss of $5.2 billion [1]. Sichuan earthquake in 2008, having magnitude of 8.0 caused 70,000 casualties, 216,000 structural failures, including 6890 school structures [2]. In Nepal earthquake of 2015, 0.15 million people were displaced due to severe structural damages in the affected region [3]. The primary reason behind the destruction of masonry buildings either partial or full, is usage of conventional unconfined masonry technique. In addition, because of design deficiencies the majority of the brick masonry buildings face severe damages during earthquakes. In 2010 Haiti earthquake, 80% to 90% of the masonry structures were declared partially or fully damaged by the Haiti government [4]. In the 2010 Darfield earthquake, damage to chimneys, collapse of parapet walls, out-of-plane failure, failure of facade wall, partial in-plane and mid height damages were observed in unreinforced masonry walls of the city [5]. In Gorkha earthquake, number of 0.5 million masonry buildings were entirely collapsed and other 0.2 million were partially damaged [6]. During the quakes of 2010 and 2011 in Canterbury, 72% of the identified walls were damaged due to out of the plane damages and 28% were due to in plane damages [7].

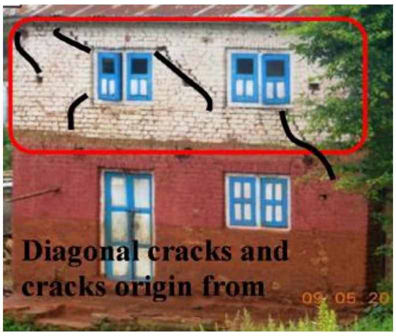
In developing countries, earthquake resistant and economical housing in the earthquake prone areas is the demand of time. Due to absence of earthquake resistant construction techniques, these countries grieve from huge human loss during strong ground motion. The literature indicates that, various construction techniques in the form of structural components for the construction of earthquake resistant masonry buildings have been adopted. For example, provision of vertical stiffeners and lintel beams in the masonry walls. Similarly, Ali et al. [8] developed mortar free interlocking block structure as a new construction technique for earthquake resistant houses and reported energy dissipation due to comparative movement at the interlocking block edges. Coconut fiber reinforced interlocking mortar-free block with post-tensioned coconut fiber ropes were tested against dynamic loading [9]. Khan et al. [10] proposed usage of interlocking plastic blocks for seismic proof housing due to their less weight in combination with energy dissipation due to uplift of blocks.

For dynamic analysis, usage of shake table in the laboratory is very well known. Modern countries are using complex 3D shake tables, while developing countries are mostly using 1D shake table because of its low cost. Dynamic behavior of prototype structures has been investigated by many researchers by using the shake table. Available literature withholds various scale down techniques to convert a real-life structure to prototypes with simplified boundary conditions. Testing of prototype structures along with analytical validation has been done by many researchers. The percentage error gives the accuracy of analytical validation as well as predicts the probable actual scenario in case of real earthquake phenomena. Nadir et al. [11] performed 44 tests on single storey structure by using shake table to study the behavior of structure under harmonic loading and reported increase in base shear. Chen et al. [12] conducted experiments on a quarter scale frame structure using shake table and indicated that the proposed control strategy of prototype was useful in oppressing the drift between storeys and acceleration of the structure's floors. Similarly, a lot of researches have been done in the past, conducting the small-scale tests to study the actual dynamic behavior in the laboratory.

II. DAMAGES OF CONVENTIONAL MASONRY STRUCTURES DURING EARTHQUAKE

Destruction of conventional masonry buildings in the form of various failures have been reported by many researches. Sharma et al [13] conducted reconnaissance study after the April 25, 2015, Gorkha earthquake in Nepal. Approximately 0.8 million partial or full collapsed buildings were reported. A severe seismic event followed by major aftershock struck the whole district having hilly area, which resulted in the destruction of many brick masonry buildings. Many people were died, injured and remained homeless till the rescued operations done by the governing authorities. Apart from this, country faced a huge economic loss from this catastrophe. Various brick masonry failures in the form of vertical cracks near the corner, crosswise cracking initiated from edges of the openings, out of plane failure, gable wall failure, separation of wall vertically and opening in short wall were reported as shown in the Fig. 1.The major reasons behind these brick masonry failures were reported as poor construction practices, poor materials usage, non-designed building walls, gable walls without confinement, and cracking initiated from edges of the openings. For retrofitting of partially damaged masonry buildings, reinforcement or provision of verticals and horizontal bands was suggested. It was also recommended to enforce code compliance and to involve experienced engineers in all design phases of the building.

(a) 

(b) 

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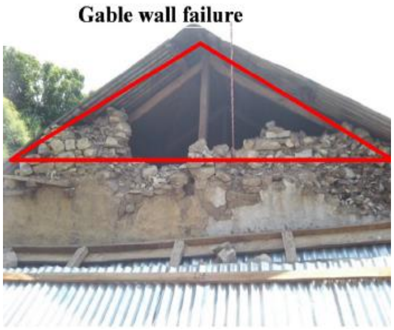
(d) 

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Fig. 1: Conventional masonry failures; (a) Vertical cracks near the corner, (b) Crosswise cracking initiated from edges of the openings, (c) Out of plane failure, (d) Gable wall failure, (e) Opening in short wall, (f) Separation of wall vertically [13]

Jagadish et al. [14] reported that traditional masonry structures suffered considerable damage during the Bhuj earthquake of January 2001. Most of the masonry structures were reported had zero earthquake resistant features, due to which these structures faced severe damages. Most common found failures in the masonry structures were out-of-plane collapse, cracks below bands, out-of-plane failure of wall leading to collapse of lintel band, collapse of wall between openings and rigid box-like behavior above lintel band. It was highlighted that mud mortar or lime mortar usage resulting in weak bond strength was the primary cause of these failures. In case where cement mortar was used in masonry, bond strength was not sufficient to resist the earthquake vibrations. The most concerned issue was the failure of confined brick masonry in the form of cracks below lintel band and collapse of lintel band. Because properly designed confined brick masonry having horizontal/verticals bands with corner reinforcement properly resists the earthquake shaking. It was found during the survey that lintel bands were not properly designed and were having deficient longitudinal reinforcement. The study suggested that, though the horizontal bands lessens the in-plane shear and verticals cracks but these may not be helpful in case of out-of-plane flexure failure. Especially flexure cracks which propagates horizontally and results in out-of-plane failure of the wall.

Fiorentino et al. [15] reported that the effect of the two seismic events of August 24th 2016 on the district of Amatrice was exceptionally disastrous. There were 298 fatalities, 386 harmed, around 5000 homeless people, and the ancient hub of the town suffered an extraordinary destruction. 260 recorded strong ground motions were analyzed, plotted in the shake map and later on compared with the large-scale damage surveys conducted in the vicinity areas. Based on an assessment study made in September 2016, a guide of the failure patterns of the structures in the ancient hub of the town was explained as per European Macroseismic Scale (EMS-98). The harm level was found extremely high with over 60% of the investigated structures demonstrating minor or complete failure. The high degree of destruction was fundamentally brought about by the high ineffectiveness of the masonry structures resulted due to poor quality material usage, absence of connections between the walls and improper connection between walls and floors. The study suggested that the importance of good engineering evaluations in the design involvements on existing buildings is very much important, which cannot just be done in light of standard methods. Perhaps, it requires a point by point assessment of local and global behavior of the building along with material testing.

III. New approach for earthquake-resistant structures

Ali [9] examined the impact of post-tensioned coconut-fiber ropes in controlling uplift of interlocking mortar free blocks construction during seismic loading. It was reported that proposed interlocking block shown in Fig. 2 is capable of regaining its original position after the induced ground motion due to provided inclined key shape in the block. A mass of 200 kg was lumped at the top of column made up of interlocking blocks, to simulate single degree freedom system. The dynamic behavior of interlocking blocks column was measured in terms of tempted accelerations, block uplift, top relative displacement and rope tension. It was found that tempted acceleration was increased up to the column mid-height and then decreased a little bit at the column top. The trends of block uplift and rope tension were found fairly similar. Experimental results were used to develop the empirical relation in the form of function of peak ground acceleration. 35% difference was observed in predicting the actual seismic response of the structure, which may comply due to the complexity of the interlocking block column. Results of the study seemed favorable in order to have economical earthquake-resistant housing construction.

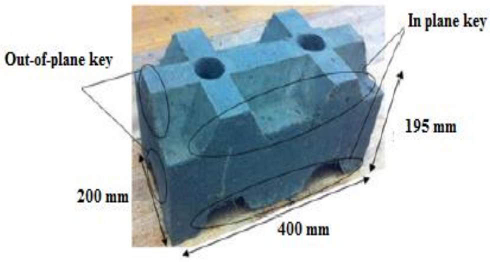


Fig. 2: Coconut Fibre Reinforced Concrete (CFRC) interlocking block [9]

Liu et al. [16] examined the cyclic behavior of non-interlocking mortar less brick and interlocking mortar less brick shown in Fig. 3. The effects of interlocking shapes, loading compression stress levels and loading cycles were considered during the investigation of cyclic behavior. With the help of hysteresis loop method, a mechanical model was established. The shear failure modes of all of the inspected joints were described by using Mohr-Coulomb failure method. With an increase in the loading cycle, there was a decrease in the friction coefficients of all of the joints. The degradation rate of the friction coefficients increased with the reduction in the smoothness of the interlocking surface.

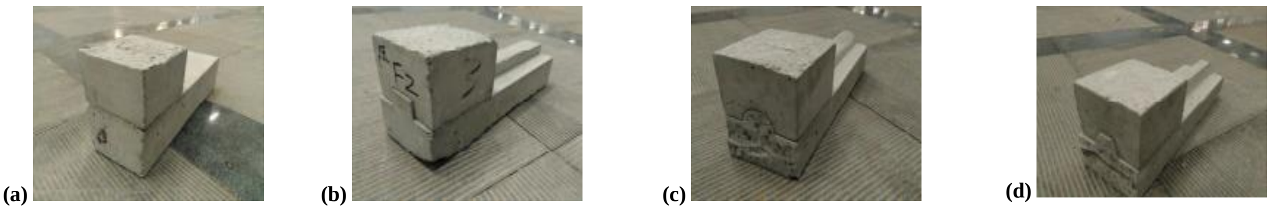


Fig. 3: Interlocking blocks with non/various interlocking patterns; (a) non-interlocking, (b) rectangular interlocking, (c) circular interlocking, (d) trapezoidal interlocking [16]

Many researchers have proposed different shapes of interlocking compressed earth block as shown in the Fig. 4. These blocks provide resistance to the movement both in horizontal and transverse direction to the wall surface. Expect, hydraform interlocking units provide straight movement and restricts crosswise one. Although these interlocking blocks have different forms, shapes and sizes but their interlocking mechanism is quite similar, consisting of protrusions and depressions also know as male and female features. Because of the complex arrangement of these blocks, the soil characteristics and curing conditions caused difficulty in keeping the precise shape and size of these interlocking blocks. A probable procedure needs specific apparatus and excellent mud choice, mix design and good curative conditions. But usage of such apparatus is uneconomical and and not available in developing countries. The study suggested another useful solution in the form of simplifying the interlocking block configuration keeping control of the geometry during the manufacturing phase. The governing factor to make straight and stable block wall is effective locking of these blocks which can resist the governing forces [17].

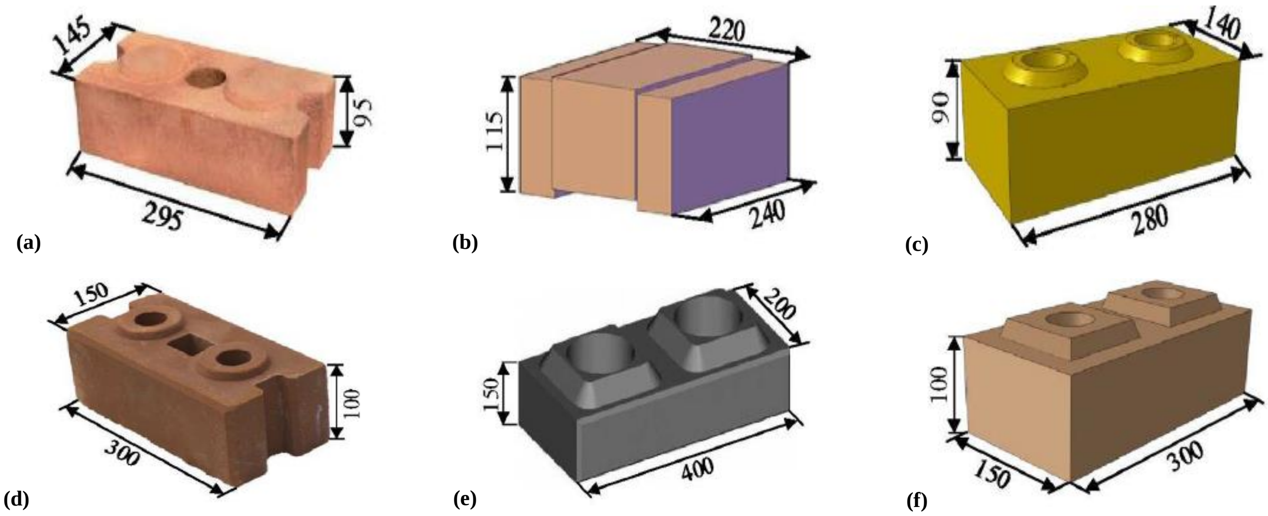


Fig. 4: Various interlocking earth blocks; (a) Auram interlocking block [18], (b) Hydraform interlocking block [19], (c) HiLoTec interlocking block [20], (d) Thai Rhino interlocking block [21], (e) Hollow interlocking block [22], (f) Tanzanian interlocking block [23]

Table 1: Summarized details of various interlocking compressed earth blocks proposed in previous researches

Reference	Interlocking block shape	Surface area of holes %	Cement content	Main findings
Maini et al. [18]	Auram block	9.2	5	Dry compression, shear and bending compressive strength; absorption of water.
Uzoegbo et al. [19]	Hydraform block	0	5-20	Compressive strength of the masonry units; compressive strength of the dry-stack walls.
Sturm et al. [20]	HiLoTec block	10	9	Compressive and flexural strength of the units; compressive and shear behavior of masonry prisms.
Qu et al. [21]	Thai Rhino block	12.7	6.2	Stress–strain curves of prisms; seismic performance of flexure-dominated interlocking compressed earth block walls; the structural performance of interlocking compressed earth block walls under cyclic in-plane loading.
Fay et al. [22]	Hollow block	28.2	9	Resistance of compression, water absorption, and sizing of interlocking compressed earth blocks.
Bland et al. [23]	Tanzanian block	8.72	7.1	Block irregularity and implication for wall quality; the relationship between alignment and block geometric imperfection; stiffness of the interlocking block columns.

Mortar less interlocking block construction has been adopted partially in different countries but with limited research background. The primary problem associated with these blocks is their production, which needs sophisticated machineries. But the salient features of the interlocking masonry are very well acknowledged in the literature. And very limited simplified and economical production techniques are proposed by the researchers. The construction industries of developed countries are acknowledging the benefits of these interlocking blocks for masonry construction. This new interlocking technique is less laborious and does not require mortar pasting activity, ultimately speeding up the construction time. In these countries, the commercially available interlocking blocks differ in shape, size, and material usage. These blocks have been categorized as ones, which confirm vertical and horizontal or only partial vertical interlocking. In some cases, to improve the lateral resistance, plain and reinforced grouting in combination with surface bonding is also in practice in masonry construction works. Previous researches have strongly recommended interlocking-block masonry system as a potential alternate to mortar-bedded masonry as it speed up the construction process and also exhibits better or comparable structural performance. But the point of concern about the usage of these earth compressed or concrete blocks is their high mass, causing greater inertia forces.

IV. Effect of Stiffeners on Masonry Construction

Brick masonry is one of the oldest and extensively adopted construction technique. The provision of brick masonry structural members in ancient buildings is also abundant. Throughout the world, unreinforced brick masonry buildings are continuous threat to mankind, due to their high vulnerability to seismicity [24]. The economic and human losses in the past earthquakes was mostly due to these vulnerable structures. These structures were constructed with conventional materials and by considering the gravity loading only [25]. These materials in majority of the cases are bricks, stones and wood, which are not earthquake-resistant [26]. During the October 2005 earthquake in Pakistan, most of the conventional unreinforced buildings including concrete block masonry, brick masonry and stone masonry were fully or partially damaged [27]. Similarly, separation between the roof diaphragms and the masonry walls (in the out-of-plane direction) and damage to masonry piers at upper levels of unreinforced masonry buildings were observed in the 2010 Darfield (Christchurch, Nz) Earthquake [28].

A French structural engineer and contractor, Paul Cottancin, introduced stiffeners to reinforce the masonry buildings at the end of 20th century [29]. Seismic behavior of masonry structures is studied in laboratory by many researchers in the past. Immense non-linear behavior of unreinforced masonry was observed in the laboratory testing under time-scaled Nahnni earthquake 1985 [30]. On contrary, reinforced brick masonry in the form of concrete stiffeners usage enhanced strength and stiffness of the masonry buildings [31]. These phenomena have been confirmed not only through lab testing but also in the case of real earthquake loading. The failure modes during the laboratory testing changed from shear slip or diagonal tension into a combination of diagonal tension and toe-crushing. Incorporation of reinforcing elements in mortar joints prevented the structure from cracking [32]. Confined masonry walls with horizontal stiffeners performed well compared to non-confined walls when subjected to lateral loading in laboratory. Masonry walls with vertical stiffeners in terms of steel ties had significant enhancement in seismic capacity in comparison with unreinforced walls [33].

Mexico country has a long record of using confined masonry technique in their housing construction. It is the most common construction practice in the country, and is widely used in the central part of the country. Confined masonry is usually practiced in the form of engineered and non-engineered construction all over the country. Most of the non-engineered construction found in the rural and sub urban areas, whereas engineered constructed buildings found in the industrial areas and developed housing schemes as shown in the Fig. 5 (a). During the 2003 Tecomán earthquake of magnitude 7.6, confined masonry buildings performed considerably better than unreinforced brick masonry buildings; majority of confined masonry buildings were undamaged or suffered only a minor damage as shown in Fig. 5 (b). Some cases of failure were observed when the number and arrangement of confining elements were inadequate as shown in Fig. 5 (c) [34].

Fig. 5: Confined masonry construction in Mexico (a) an engineered structure in the industrial zone, (b) minor damage of confined masonry (c) major damage of confined masonry due to inadequate confining elements and their arrangement [34]

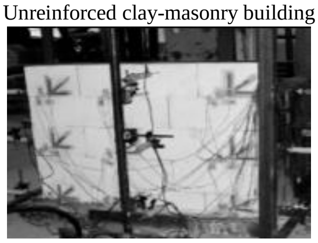
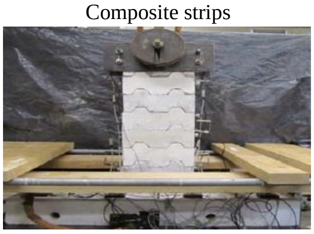
Similarly, confined masonry buildings performed exceptionally well in the El Salvador earthquakes of 2001 [35]. Confined masonry structures are very common in El Salvador. Almost 60% of the structures in El Salvador were constructed from mixto, a type of confined masonry with closely spaced tie-beams and small tie-column spacing. Over 90% of the buildings of this type were undamaged; only 5.9% of confined masonry or concrete buildings faced repairable damage, whereas 2.4% of the buildings were damaged beyond repair. Among the damaged buildings of this type, there were a few cases of wall shear failure, as well as out-of-plane wall failures, where the wall toppled outwards in spite of the confining elements. The study concluded that most of the damaged or collapsed structures during the earthquakes were of conventional masonry construction [36].

Fig. 6: Behavior of confined masonry during the 2001 El Salvador earthquakes, (a) confined masonry structures in city of Santa Cruz Analquito survived, whereas nearby conventional structures was destroyed, (b) a confined masonry school building survived the earthquake without damage (c) soft story construction (confined masonry construction at the ground floor level) [36]

V. Dynamic performance of prototype-structures in lab

Significant research has been conducted in the past to study the behavior of real-life structures with the help of scaled down prototypes in the laboratory. 3-D shake table having six degree of freedom is used in developed countries to investigate the dynamic response of structure, in order to generate real earthquake data. On the other hand, developing countries lack in affording such sophisticated and expensive complex 3-D shake table. But these countries are using simple 1-D to understand dynamic behavior of prototype-structures in laboratory. The purpose behind development of prototypes structures in laboratory is to conduct such studies. For determination of seismic behavior of these prototypes under dynamic loading, time history analysis is a useful technique [37]. Elvin et al. [38] studied the behavior of full-scale structure under harmonic loading. The dynamic analysis of a prototype structure was conducted in laboratory. And it was reported that structural damages due to earthquake can be reduced, if structure is properly designed to resist earthquake loading [39].

Table 2: Summarized details of dynamic testing of various prototype structures using shake table in previous researches

Reference	Prototype structure	Main findings
Elvin et al. [40]	 Dry-stack masonry wall	The earthquake and harmonic base motion energies were dissipated through inter-brick friction, and in some cases by bricks cracking and crushing. The fact that the bricks were dry-stacked allowed them to move and hence dissipate energy.
Kallioras et al. [41]	 Unreinforced clay-masonry building	The study provided a unique data set that captures at full scale the in-plane and out-of-plane behavior of unreinforced masonry walls, and the influence of flexible diaphragms on the dynamic global response of a complete building under dynamic loading.
Saifee et al. [42]	 Interlocking mortar less wall	Interlocking mortar less wall was subjected to out of plane loading. The behavior of dry joint openings the wall was judged. The dry joint opening mechanism around mid-height of wall was reported to be dominant.
Velazquez-Dimas et al. [43]	 Unreinforced Masonry wall with Glass Fibre Composite strips	URM wall strengthened with the help of glass fibre strips was tested and results was compared with the developed analytical model. The study suggested to limit maximum service load to a corresponding strain of 0.004.
Ali [9]	 Mortar-free Interlocking block column with post tensioned Coconut-fibre ropes	In this study, coconut fiber reinforced interlocking mortar-free block with post-tensioned coconut fiber ropes were tested against dynamic loading. Energy dissipation because of the relative movement at the block interfaces was reported.
Antonellis et al. [44]	 Bridge columns supported on rocking shallow foundations	The test protocols included up to six historical ground motions and resulted in peak drift ratios up to 13.8%. For peak drift ratios up to 6.9%, the rocking foundations performed very well, with residual drift ratios between 0.5 and 0.9%.

VI. CONCLUSIONS

Conventional masonry structures are prone to earthquake. Modern countries have adopted the practice of confined masonry in their construction techniques. But these are also prone to earthquake vibration up to some extent. Researchers are focusing on interlocking mortar free blocks as a replacement of brick masonry. Available literature has featured a lot of sizes, shapes and interlocking techniques for these blocks. In the laboratory, examining the dynamic behavior of interlocking block prototype structures using the shake table gives output at a higher accuracy level. The behavior of these interlocking block prototypes against dynamic loading can be predicted better by conducting small scale testing. Their analytical validation can be used to develop empirical relations in order to perform simplified testing with the identification of error percentages. A lot of researches support and validate the results obtain from the testing of these prototype structures. Most of the researchers till date have focused on concrete block or masonry block studies. But usage of any other light weight material can play a vital role in reducing the inertial forces.

VII. RECOMMENDATIONS

Empirical relations to support simplified testing with boundary conditions and to bridge the gap between actual scenarios and prototype testing needs to be explored in detail. Instrumentation of test setups to get accuracy for results is an important aspect to be covered in researches. Commercialization and production of various interlocking blocks is problematic due to non-engineered mentality of local contractors, unavailability of machinery and well-trained labor. The aspect regarding the commercialization needs to be investigated to make these blocks available commercially for use in construction industry. On the other hand, relatively skilled labor can be trained to produce these interlocking blocks at local level.

VIII. ACKNOWLEDGEMENTS

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