Design Procedure for Semi Interlocking Masonry

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Abstract: SIM (semi interlocking masonry) is a kind of innovative building system for mortar-less walls. It utilizes a special method of interlocking SIM bricks that allows relative sliding of brick courses in-plane of a wall and prevents out-of-plane relative movement of bricks. It has increased capacity to dissipate earthquake energy through friction between bricks compared with traditional masonry. It can be used in earthquake resistant frame structures as infill panels, which also act as EDD (energy dissipation devices). However, as a mortar-less system, it is not covered by masonry design standards. The purpose of this paper is to introduce SIM and also to develop an analytical design procedure for this innovative masonry system.

Key words: Semi interlocking masonry, mortar-less system, earthquake resistance, EDD.

1. Introduction

Masonry is one of the most popular building materials. Over time masonry structures have evolved from massive walls, which work mainly in compression, to more slender walls, which could also experience tension and shear. Earthquake-induced tensile and shear stresses often exceed capacity of traditional unreinforced masonry resulting in substantial damage and failure. Reinforced masonry has better earthquake resistance, however, it is more expensive and requires expertise not always available in developing countries. The design of practical masonry with improved earthquake resistance still presents a challenge for structural engineers. The author has developed a new masonry system. It is called SIM (semi interlocking masonry). It has reduced stiffness and susceptibility to damage and increased capacity to dissipate earthquake energy compared with traditional masonry.

SIM is an innovative building system for mortar-less walls. It utilizes a special method of interlocking SIM bricks that allow relative in-plane sliding of brick courses of a wall and prevents out-of-plane relative movement of bricks.

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Two different methods of semi interlocking have been developed:

- using specially shaped bricks (“topological SIM”);
- using conventionally shaped bricks with special perforations and dowels (“mechanical SIM”) (Fig. 1).

Traditional brick moulding technology can be easily adopted for making topological SIM units. Mechanical SIM units are designed to utilize existing brick extrusion technology. The structural performance of these two SIM types is essentially identical [1]. Topological SIM, however, appears to have better resistance to water penetration [2].

Several possible structural and non-structural applications of SIM include:

- infill panels in multi-storey frame structures;
- walls in confined masonry structures;
- masonry skins of a reverse brick veneer systems;
- robotically prefabricated masonry walls;
- DIY (do it yourself) masonry;
- demountable masonry structures.

This paper, however, will be focused on the design of SIM panels for earthquake resistant multi-storey frame structures.

1.1 Novelty of SIM and Comparison to Other Interlocking Masonry Systems

There are many different interlocking brick/block

Fig. 1 Different methods of semi interlocking: (a) topological; (b) mechanical.

masonry systems on the market. They are all developed to build structural or non-structural walls without mortar. Some of them are dry set like SIM and others use various adhesives to bond units into a monolithic wall. The main difference of SIM is that, unlike all of these systems, it avoids connecting units into a monolith. Its purpose is quite the opposite: it makes walls pliable and deformable. To better explain the novelty of SIM, let us recall the definitions of a structure and a mechanism. A structure is a body or an assembly of bodies to form a system capable of supporting loads. A mechanism is an assembly of moving parts capable of performing a complete functional motion. SIM is designed for relative motion of bricks without necessarily supporting loads. Therefore, SIM walls are not structures but energy dissipating mechanisms.

1.2 Origin of SIM and Historical Background

The author invented the system in 2010 [3] and first introduced it in print in 2011 [4]. Various elements of it are not new. In fact, one could trace their heritage to the dry set stone masonry of Mesolithic era with elements of interlocking such as mortise-and-tenon joints of Stonehenge. Another ancient example of topologically interlocking masonry is multifaceted stones of Machu Picchu. Ancient Egyptians, Romans, Incas and Khmers used metal masonry block connectors. Slotted holes are very common in steel construction for relative sliding of connected parts. The concept of a masonry wall

designed not as a monolith structure but as a mechanism where bricks slide against each other is entirely new, however.

1.3 Previous Research on Dry Stack Masonry

Some research has been done previously on dry stack masonry. Lourenco et al. [5] and Lourenco and Ramos [6] with his colleagues performed a series of tests and concluded that the failure criteria of dry stack stone are type of Mohr-Coulomb failure. A number of cyclic tests and shaking table tests both on dry stack stone and mortar stone wall were also carried out [7-9]. From those tests, the type of wall boundary conditions and the vertical compression level were confirmed as two important factors for the failure mode. Considerable nonlinear deformations have been attained (storey drift of 2.5%). However, because of the rocking failure mechanism, they concluded that unframed dry stack walls were unable to dissipate energy.

Uzoegbo [10] and Uzoegbo et al. [11] have researched on both in-plane and out-of-plane seismic behavior of dry stack masonry wall. According to their research, the strength of dry stack units does not make a significant difference in the resistance to lateral loads: the interlocking and friction between units govern the lateral load bearing capacity. The compressive strength of the panel is directly proportional to the strength of masonry units. They also observed rocking of the dry wall before failure. A shake table test has been

conducted on the dry stack system, which demonstrated that the dry stack masonry structure could resist the ground acceleration of up to 0.3g [12].

1.4 Previous Research on SIM

The author and his colleagues at the University of Newcastle in Australia and Harbin Institute of Technology (Shenzhen Graduate School) conducted all previous research on framed SIM infills.

Initial tests on SIM included compressive tests on SIM units and SIM prisms. Cyclic friction tests on SIM triplets [13] were performed using modified triplet shear test [14]. The average friction coefficient of 0.66 was determined for concrete SIM units at clamping stress of 0.1 MPa to 0.5 MPa. However, at higher level of the clamping stress, the friction coefficient reduces to 0.55. This value is recommended for analysis as more conservative. In-plane cyclic displacement tests were performed on the full-scale reduced size RC (reinforced concrete) frame infilled with prototype “SIM with closing gap” panel (2 m × 2m; Type 3; 227 mm × 113 mm × 80 mm concrete units). Detailed results are reported in Refs. [4, 15]. These tests identified three main response mechanisms for a frame with SIM infill panel: (1) constant friction response; (2) Mohr-Coulomb response; (3) plastic response. In-plane cyclic displacement tests were performed on the full-scale reduced size steel frame infilled with two different SIM panels: “with open gap” (Type 1) and “without gap” (Type 2) (both 2.4 m × 2.4 m made of 230 mm × 110 mm × 76 mm concrete units). These tests confirmed in-plane response mechanisms. Out-of-plane monotonic airbag test was performed after the last cyclic test on the same panel. The out-of-plane displacement capacity of the square SIM panel of Type 2 was more than 1.5 times the thickness of the panel. Detailed results are reported in Ref. [16]. All in-plane cyclic tests also provided experimental data for calculation of the frictional energy dissipation and estimation of damping.

Numerical modeling of SIM panels was done using

the microstructural approach (Diana FE (finite element) software [17]) and the super-element approach (SeismoStruct FE program [18]). Both models were verified using experimental results described above. SeismoStruct was selected for numerical simulations for multi-storey frames as more practical program. Four FE models were created for tree bay four-storey RC frame:

- RC frame without infill panels;
- RC frame with “open gap” (Type 1) SIM infill panels;
- RC frame with “no gap” (Type 2) SIM infill panels;
- RC frame with traditional URM (unreinforced masonry) infill panels.

The non-linear analysis due to monotonic load (pushover analysis) and the response history analysis under synthetic earthquake ground motion [19] determined the yield displacement, the ultimate displacement, and the structural displacement ductility for all models as well as confirmed earthquake resistant effect of SIM.

2. Design Procedure for SIM Infill Panels

SIM infill panel is a kind of wall and as such must be designed to perform typical architectural functions: providing shelter, security and dividing internal space. Properties such as sound insulation, fire resistance, thermal conductivity, water penetration, etc., however, are beyond the scope of the following discussion, which will be limited to the engineering design of SIM infill panel only.

2.1 Structural Application of SIM As Infill Panels

SIM is an innovative building system that uses engineered mortar-less masonry panels to improve energy dissipation of frame structures during earthquakes. The energy dissipation occurs through friction between bricks as they engage in relative sliding by the frame vibrating during earthquake. The more earthquake energy friction diverts to heating the

structure, the less would remain to cause structural vibration and damage.

SIM panels are suitable for inclusion in new earthquake resistant structures as well as seismic rehabilitation or retrofitting of existing structures.

The frame could be of reinforced concrete, steel or other structural materials. SIM bricks could be pressed or extruded of concrete or structural clay. SIM panel could be single-skin, double bricks, or cavity wall within the plane of the frame. SIM panel could be an unreinforced dry stack wall with the running bond masonry pattern or it could also be post-tensioned through aligned vertical perforations in SIM bricks. Despite this multitude of design options for the frame/SIM panel combination, the following discussion will be focused on frames with single-skin concrete SIM panels.

A narrow gap between the top of SIM panel and the frame girder is difficult to avoid during construction of panels within the frame. Special packing should be used when this gap is undesirable. The presence of this gap and its width play a key role in the structural response of SIM panel to earthquake-induced vibrations. There are three main types of SIM panels:

- “SIM with open gap” or SIM Type 1. This type of SIM panel is built hard against the columns, however, has the gap between the top of the panel and the girder. The frame interacts with the SIM panel only through columns. The gap does not close during earthquake-induced vibrations. Frame girders never clamp SIM panel of this type in vertical direction. It mainly provides energy dissipation to the structure. Its strengthening effect is limited to the maximum friction force developed on the bead joints of the panel due to self-weight;

- “SIM without gap” or SIM Type 2. There are no gaps between this type of SIM panel and the frame. It is in contact with the girder as well as columns. Therefore, panels are clamped between girders at all amplitudes of vibrations. This has dual effect of: (1) providing some bracing to the frame through the diagonal clamping

zone; (2) providing higher level of energy dissipation compared to the previous type of SIM panel due to higher compression/friction on the bead joints;

- “SIM with closing gap” or SIM Type 3. This is a combination of the first two types. It has a very narrow gap between the top of the panel and the girder. This type of SIM panel mainly provides energy dissipation to the structure during small amplitude vibrations when the gap remains open. However, as the amplitude increases, the gap closes, the clamping is activated, and the panel begins to provide additional bracing to the frame as well as higher energy dissipation.

2.2 Novelty of SIM Frame Infill

Traditional masonry infills are either architectural walls or structural panels designed to brace frame structures. They are not intended for energy dissipation. Energy dissipation in these infills during earthquakes mostly relates to the micro and macro structural cracking and plastic behavior of material. The capacity of traditional infills to dissipate energy in this way before failing is quite limited.

The novel purpose of SIM infill panels is to provide frame structures with artificially added damping. In SIM panels, energy dissipation occurs mostly through friction between bricks of the panel. SIM is a unique system, which utilizes masonry infills as effective EDD (energy dissipation devices) to improve earthquake resistance of frame structures.

Superficially, an SIM infill looks like any other masonry infill panel. However, it is conceptually different from all other masonry infill types. Let us consider the classical equation of motion for a structure under earthquake load to demonstrate this difference:

$$\mathbf{k}\mathbf{u} + \mathbf{c}\dot{\mathbf{u}} + \mathbf{m}\ddot{\mathbf{u}} = -\mathbf{m}\ddot{\mathbf{u}}_g(t) \quad (1)$$

where, $\mathbf{u}$ is the vector of dynamic displacements (vibrations); $\dot{\mathbf{u}}$ is the vector of velocities, $\ddot{\mathbf{u}}$ is the vector of accelerations, $\ddot{\mathbf{u}}_g(t)$ is the acceleration of the ground, $\mathbf{k}$ is the stiffness matrix, $\mathbf{c}$ is the damping matrix, and $\mathbf{m}$ is the mass matrix. All common types of

masonry infills are structurally various forms of frame bracing. They minimize vibrations mainly by increasing the stiffness of the structure represented in the above equation by the stiffness matrix. Often, this is achieved at the expense of lowering the yield displacement and displacement ductility of the structure. SIM infills also aim to minimize vibrations but in a different way. Being energy dissipation devices, they achieve this objective by changing the damping matrix without detrimental effect on the yield displacement and displacement ductility of the structure.

It is important to stress that SIM infill panel is not a frame bracing structure but a mechanical energy dissipation device and must be designed accordingly. Basic principles and current design philosophy for this type of energy dissipation devices are presented in Ref. [20]. A good design procedure for passive energy dissipation devices like SIM panel is outlined in Ref. [21]. This document also provides recommendations for testing such devices.

Damping effect afforded by SIM panel could be calculated as follows:

$$\zeta_{ef} = \zeta_{frame} + \zeta_{SIM}^* = \zeta_{frame} + \frac{U_{SIM}^F}{4\pi U_{frame}^S} \quad (2)$$

where, ζ_{ef} is the effective damping in the structure, ζ_{frame} is the hysteretic damping in the frame only (typically taken as 5%), ζ_{SIM}^* is the equivalent viscoelastic damping for SIM panels (about 8.5% [22]), U_{SIM}^F is the frictional energy dissipation in all SIM panels during one cycle of vibrations at designed target displacement, and U_{frame}^S is the maximum strain energy in the frame.

In the standard procedure of direct displacement based design, increasing the effective damping of the structure would increase its effective stiffness for the same target displacement. This would allow savings made by reducing cross sections and reinforcement of the frame. Practically, the design procedure is about calculating the frictional energy dissipation in all SIM panels U_{SIM}^F during one cycle of vibrations for use in Eq. (2).

2.3 Frictional Energy Dissipation in SIM Panels during In-plane Vibration

Frictional forces exist in all joints in SIM: bead joints and head joints. However, for the following calculations, the author makes a conservative assumption that frictional forces on head joints are considerably smaller than those on bead joints and can be ignored. Following calculations obviously do not account for the frictional energy dissipation on bead joints due to relative rotation of SIM units during out-of-plane deflection of a panel, which is expected to be significant. For the purposes of calculation of the frictional energy dissipation, frictional forces due to self-weight of the panel are considered as a set of gradually increasing from the top to the bottom of the panel horizontal point loads, not as a triangular distribution.

2.3.1 SIM Panel with Open Gap (Type 1)

The friction forces on a bead joint between two brick courses in this panel type are due to the weight of the panel above the joint. The maximum frictional force is at the bottom of the panel due to its total weight:

$$F_{max}^W = H \cdot L \cdot t \cdot \rho \cdot g \cdot \mu \quad (3)$$

where, H is the height of the panel, L is the length of the panel, t is the thickness of the panel, ρ is the density of the panel's material, g is the acceleration due to gravity, and μ is the coefficient of friction. The friction force on the i th bead joint, counting from the top, is:

$$F_i^W = F_{max}^W \frac{ih}{H} \quad (4)$$

where, h is the brick height. Assuming a uniform distribution of the relative slip between brick courses due to the panel distortion, on the i th bead joint, it can be expressed through the target storey drift Δ_i as follows:

$$\delta_i = \Delta_i \frac{h}{H} \quad (5)$$

Each bead joint of Type 1 SIM panel acts as a typical frictional damper with a rectangular load-displacement hysteretic curve. Then the frictional energy dissipation on the i th bead joint due to self-weight of the panel

above it, as shown in Fig. 2, is:

$$U_i^F = 4A = 4F_i^W \delta_i \quad (6)$$

where, A is the shaded area in Fig. 2.

The total frictional energy dissipation in a SIM panel due to its weight during one cycle of vibration at the target storey drift is the sum of energy dissipation on all bead joints in the SIM panel:

$$U_{SIM}^F = \sum_{i=1}^{H/h} U_i^F = \sum_{i=1}^{H/h} 4F_i^W \delta_i = \sum_{i=1}^{H/h} 4F_{\max}^W \frac{ih}{H} \Delta_t \frac{h}{H} = 2F_{\max}^W \Delta_t \left(1 + \frac{h}{H}\right) \quad (7)$$

2.3.2 SIM Panel without Gap (Type 2)

The friction force on the i th bead joint between two brick courses in this panel type is the sum of the friction force due to the weight of the panel (as for panels of Type 1), which varies on different joints and the friction force due to the vertical compression of the weightless panel by the distorted frame, which is constant on all joints. Assuming that the compression is induced over the half of each bead joint (for the top raw of bricks, for example, from the upper panel corner to the point of contra-flexure of frame girder), this constant component of friction force F^C at target storey drift can be calculated as follows:

$$F^C = \sigma^C \frac{L}{2} t \mu = E_{SIM} \varepsilon^C \frac{L}{2} t \mu \approx E_{SIM} \frac{\Delta_t^2}{2H^2} \frac{L}{2} t \mu = \frac{E_{SIM} \Delta_t^2 L t \mu}{4H^2} \quad (8)$$

where, σ^C is the vertical compressive stress on bead joints, ε^C is the corresponding compressive strain, and E_{SIM} is the compressive elastic modulus of SIM. The friction force on the i th bead joint, counting from the top, is:

$$F_i^F = F_i^W + F^C = F_{\max}^W \frac{ih}{H} + \frac{E_{SIM} \Delta_t^2 L t \mu}{4H^2} \quad (9)$$

Then the frictional energy dissipation on the i th bead joint due to combined effect of self-weight of the panel above it and clamping by the frame, as shown in Fig. 3, is:

$$U_i^F = 4A_1 + 2A_2 =$$

$$4F_i^W \delta_i + 2 \int_0^{\delta_i} F^C d\Delta = 4F_i^W \delta_i + 2 \frac{F^C \delta_i}{3} \quad (10)$$

where, A_1 is a quarter of the area representing the energy dissipation due to self weight and A_2 is a half of the area representing the energy dissipation due to clamping of SIM panel by the frame.

The total frictional energy dissipation in an SIM panel without gap during one cycle of vibration at the target storey drift is the sum of energy dissipation on all bead joints in the SIM panel:

Fig. 2 Frictional energy dissipation in the SIM panel with open gap on the force-displacement (P - Δ) diagram.

Fig. 3 Frictional energy dissipation in the SIM panel without gap.

$$\begin{aligned}
U_{SIM}^F &= \sum_{i=1}^{H/h} \left(4F_i^W \delta_i + 2 \frac{F^C \delta_i}{3} \right) = \\
&\sum_{i=1}^{H/h} 4F_{\max}^W \frac{ih}{H} \Delta_i \frac{h}{H} + \sum_{i=1}^{H/h} \frac{E_{SIM} \Delta_i^2 L t \mu}{4H^2} \cdot \frac{2}{3} \Delta_i \frac{h}{H} = \\
&= 2F_{\max}^W \Delta_i \left(1 + \frac{h}{H} \right) + \frac{E_{SIM} \Delta_i^3 L t \mu}{6H^2} \quad (11)
\end{aligned}$$

2.3.3 SIM Panel with Closing Gap (Type 3)

This type of SIM panel has more complex energy dissipation compared to the first two types. Because the width of the gap between the top of the panel and the girder of the frame is likely to be uneven in realistic cases, the hysteretic P - Δ curves could be non symmetric, as shown in Fig. 4. In reality, this means that, at some amplitudes of vibration, the gap would be closing during sway in one direction, say to the right, but would not close during reverse sway, say to the left. This could result in unnecessary complicated equations for the energy dissipation. Hence, the first step in the calculation procedure is replacing the uneven gap with the equivalent even gap as shown in Fig. 4:

$$\forall \bar{\Delta}_G < \Delta_i : \bar{\Delta}_G =$$

$$\frac{|\Delta_G^L| + |\Delta_G^R|}{2} = \frac{\sqrt{2Hd_{gap}^L} + \sqrt{2Hd_{gap}^R}}{2} \quad (12)$$

where, Δ_G is the storey drift required to close the gap d_{gap} is the gap widths, and superscripts L and R denote left and right.

Fig. 4 Frictional energy dissipation in the SIM panel with closing gap.

The friction force on the i th bead joint between two brick courses in this panel type is the sum of the friction force due to the weight of the panel and the friction force due to the vertical compression of the panel by the distorted frame (as for panels of Type 2):

$$F_i^F = F_i^W + F^C = F_{\max}^W \frac{ih}{H} + \frac{E_{SIM} (\Delta_i - \bar{\Delta}_G)^2 L t \mu}{4H^2} \quad (13)$$

Then the frictional energy dissipation on the i th bead joint due to combined effect of self weight of the panel above it and compression by the frame, as shown in Fig. 4, is:

$$\begin{aligned}
U_i^F &= 4A_1 + A_2 = 4A_1 + 2A_3 = \\
4F_i^W \delta_i + 2 \int_{\frac{h}{H} \bar{\Delta}_G}^{\delta_i} F^C d\Delta &= 4F_i^W \delta_i + 2 \frac{F^C \left(\delta_i - \frac{h}{H} \bar{\Delta}_G \right)}{3} \quad (14)
\end{aligned}$$

The total frictional energy dissipation in an SIM panel without gap during one cycle of vibration at the target storey drift is:

$$\begin{aligned}
U_{SIM}^F &= \sum_{i=1}^{H/h} \left(4F_i^W \delta_i + 2 \frac{F^C \left(\delta_i - \frac{h}{H} \bar{\Delta}_G \right)}{3} \right) = \\
\sum_{i=1}^{H/h} 4F_{\max}^W \frac{ih}{H} \Delta_i \frac{h}{H} + \sum_{i=1}^{H/h} \frac{E_{SIM} (\Delta_i - \bar{\Delta}_G)^3 L t \mu}{4H^2} \cdot \frac{2h}{3H} &= \\
2F_{\max}^W \Delta_i \left(1 + \frac{h}{H} \right) + \frac{E_{SIM} (\Delta_i - \bar{\Delta}_G)^3 L t \mu}{6H^2} \quad (15)
\end{aligned}$$

The total frictional energy dissipation in all SIM panels in a frame structure is the sum of individual contributions of each SIM panel calculated according to Eqs. (7), (11) and (15).

3. Conclusions

This paper introduced an innovative building system for mortar-less walls called SIM, which has increased capacity to dissipate earthquake energy through friction between bricks compared with other types of masonry. It can be used in earthquake resistant frame structures. The paper classified SIM panels based on the presence and the width of the gap between the top of the panel and the frame. The key parameter for design of SIM infill panels is the frictional energy dissipation on bead joints. The energy dissipation typical for each panel type was analyzed and a design procedure for this innovative masonry system was developed. The presented design procedure is analytical: it is based on material properties of SIM, dimensions of the panel and does not contain empirical constants.

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