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ENERGY DISSIPATION IN INNOVATIVE EARTHQUAKE RESISTANT MASONRY INFILL PANELS MADE OF SEMI INTERLOCKING BRICKS

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Abstract

This paper presents an analytical procedure for evaluation of the in-plane force-displacement characteristic and the corresponding energy dissipation of a new building system for masonry infill panels - semi interlocking masonry (SIM). SIM is a mortar-less masonry system. It utilises special methods of brick interlocking that allows relative sliding of brick courses in-plane of a panel and prevents out-of-plane relative movement. Compared to traditional masonry, it has increased capacity to dissipate earthquake energy through friction between bricks. SIM infills are intended as passive energy dissipation devices (EDDs) for earthquake resistant structures. Vibration control properties of such devices usually are determined by prototype testing. SIM panels, however, cannot be easily tested outside of the frame. In addition, being displacement-dependent EDDs, they shall be modeled in sufficient detail to capture their force-displacement response as well as interaction with primary frame elements. While the displacement capacity of SIM panels exceeds all reasonable requirements by definition, the in-plane force-displacement characteristic, which allows evaluation of the energy dissipation, must be determined. This paper presents a required procedure and demonstrates its application on different types of SIM panels. Analytical results are compared to experimental results.

Keywords: Semi interlocking masonry, mortar-less system, infill frame, earthquake resistance, EDD

1. Introduction

The main purpose of an earthquake resistant structure is to prevent loss of life by not collapsing during rare strong earthquakes. Traditional unreinforced masonry (URM) infill panels, which are very common in multistorey frame structures, are known for poor performance in past earthquakes. They are very stiff elements that attract significant horizontal forces, however, they are not always capable to resist or transmit those horizontal forces because they are not strong enough in tension and shear. Besides this, URM panels are brittle and slender; they crack at small distortion and once cracked they become unstable and collapse out of frame.

Several different design strategies could improve earthquake resistance: (i) increase the strength of the structure; (ii) increase the ductility of the structure; (iii) isolate structure from the earthquake load; and (iv) reduce earthquake induced forces by employing energy dissipation technologies. Viability of these strategies depends on many factors, including type of structural material, labour costs, available technical expertise, etc. Some of these strategies have been employed to develop new earthquake resistant masonry systems. For example, hybrid masonry [1] utilizes all the above strategies by reinforcing masonry panels, leaving gaps between panels and a structural steel frame thus isolating them from frame, and providing sacrificial steel plate connectors capable of dissipating energy after yielding. This masonry system is quite elaborate and requires expertise not always available in developing countries. The design of economical low-tech masonry systems with improved seismic behaviour still presents a challenge for structural engineers.

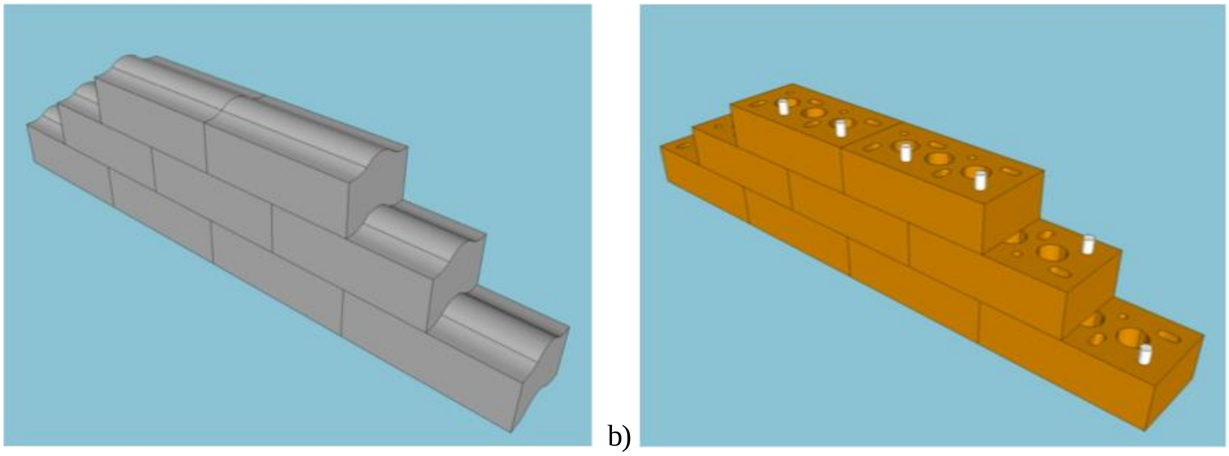
A new masonry system, which can address this challenge, has been invented by the author [2] and first introduced in print in [3]. It is called semi interlocking masonry (SIM). Several possible structural and non-structural applications of SIM include: infill panels in multistorey frame structures; walls in confined masonry structures; masonry skins of reverse brick veneer systems; robotically prefabricated masonry walls; DIY masonry. This paper, however, is focused on SIM as a new earthquake resistant masonry system for infill panels. It improves earthquake resistance of the structure by sacrificing most of the panel's stiffness to achieve lower susceptibility to damage and increased capacity to dissipate earthquake energy compared to traditional masonry.

SIM is a building system for mortar-less walls. It utilises special methods of interlocking bricks that allow relative sliding of brick courses in-plane of a wall and prevent their out-of-plane relative movement. Two different methods of semi interlocking have been developed:

- with specially shaped bricks ("topological SIM"), see Fig. 1a;
- with dowels and conventionally shaped bricks, which have special pattern of perforations ("mechanical SIM"), see Fig. 1b. The structural performance of these two SIM types is essentially identical [4].

There are several different interlocking brick/block masonry systems. They all developed for mortar-less walls. Some of them are dry set like SIM; others use 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 illustrate the novelty of SIM let us consider it through 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 functional motion. SIM is designed for relative motion of bricks without necessarily supporting loads. Hence, SIM infill panels are mainly energy dissipating mechanical devices. They also provide some bracing to the frame, however, this is not their main purpose.

Superficially, a SIM infill looks like any other masonry infill panel. However, it is conceptually different from all other types of masonry infills. Traditional masonry infills are either non-structural partition walls or structural panels designed to brace frame structures. They are not specifically intended for energy dissipation. Energy does dissipate in these infills during earthquakes but mostly due to cracking and plastic behaviour of masonry. The capacity of traditional infills to dissipate energy before failing is quite limited.



a) b)

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

The purpose of SIM infills is to provide frame structures with artificially added damping. In SIM panels energy dissipates mainly through friction between bricks. It is a unique system, which turns masonry infills from being fragile elements of a structure (susceptible to earthquake damage) into effective passive vibration control devices without sacrificing much of the infills' functionality.

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

SIM panels could be specified for new earthquake resistant structures as well as used for 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 brick, 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 visible in Fig. 1b. Despite this multitude of design options for the frame/SIM panel combination, this paper is focused on frames with single-skin unreinforced concrete SIM infill panels.

2. Classification of SIM infill panels

A narrow gap between the top of an infill panel and the frame girder is difficult to avoid during construction. The presence of this gap and its width play key roles in the seismic response mechanism of a SIM panel. Detailed classification of SIM infill panels is presented in [5]. Following is the summary of it. There are three main types of SIM panels described below.

2.1 "SIM with open gap" (type 1)

This type of SIM panel is built tight against columns, however, has the gap between the top of the panel and the girder. The interaction between the SIM panel and the frame occurs only trough panel/column interfaces. The gap narrows but remains open during earthquake vibrations. Assuming a sinusoidal shape for distortion of columns in the fundamental mode of the rigid frame vibrations, the critical gap width can be calculated. For the gap to always remain open, its width is controlled by the limit established in [5] and presented in Eq. (1):

$$d_{gap} \geq 0.34\Delta_{ult}, \tag{1}$$

where, d_{gap} is the gap width; and Δ_{ult} is the ultimate storey drift. SIM panel of this type is never clamped vertically between frame girders. It provides mainly energy dissipation to the structure. Its in-plane strengthening effect is limited to the maximum friction force developed on the bead joints of the panel due to self-weight. SIM panels of this type are mainly energy dissipating mechanisms.

2.2 "SIM without gap" (type 2)

There is no gap between this type of SIM panel and the frame, as described by Eq. (2) below

$$d_{gap} = 0. \tag{2}$$

This could be achieved in practice by using special hardening gap fillers. It is always in contact with the girder as well as columns. Hence, panels are clamped between girders at all amplitudes of vibrations. This has the dual effect of i) providing some bracing to the frame through the diagonal clamping zone and ii) providing a higher level of energy dissipation compared to the previous type of SIM panel due to higher compression and friction on the bead joints. SIM panels of this type could resist/transmit considerable earthquake induced loads as well as dissipate energy. They can be classified as mechanical structures.

2.3 "SIM with closing gap" (type 3)

This is a combination of the previous two types. It has a very narrow gap between the top of the panel and the girder, which remains open during small amplitude vibrations but closes when amplitude increases beyond certain threshold. Eq. (3) gives the gap width limits for the panel of type 3.

$$0 < d_{gap} < 0.34\Delta_{ult} \tag{3}$$

This type of SIM panel provides mainly energy dissipation during small amplitude vibrations when the gap remains open. However, as the amplitude increases, the gap closes, the clamping of the panel is activated, and it begins to provide some bracing to the frame as well as increased energy dissipation. I think, they can be called structural mechanisms.

3. Previous research on dry stack masonry including SIM

Some research has been done previously on dry stack masonry. Lourenco with his colleagues [6] after a series of tests concluded that the failure criterion of dry stack stone masonry is a type of Mohr-Coulomb failure. A number of further cyclic and shaking table tests on dry stack stone and mortar-stone walls were performed [7,8]. From these tests, the type of wall boundary conditions and the vertical compression level were confirmed as two important factors for the failure. Considerable nonlinear deformations have been attained (storey drift of 2.5%). However, because of the rocking failure of unframed walls, they concluded that dry stack masonry is unable to dissipate energy.

Uzoegbo studied in-plane and out-of-plane seismic behaviour of dry stack masonry walls [9]. According to this 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. Rocking of the dry wall before failure was also observed. A shaking table test has been conducted on the dry stack structure, which demonstrated that it could resist the ground acceleration of up to 0.3g [10].

The author and his colleagues at the University of Newcastle (Australia) and Harbin Institute of Technology (Shenzhen Graduate School) conducted all previous research on framed dry stack masonry infill panels. Initial tests on SIM included compressive tests on SIM units and SIM prisms. Cyclic friction tests on SIM triplets [11] were performed using modified triplet shear test [12]. The average friction coefficient of 0.66 was determined for concrete SIM units at clamping stress of 0.1 to 0.5 N/mm2. However, at higher levels of the clamping stress the friction coefficient reduced to 0.55. This value is recommended for analysis, as it is more conservative.

In-plane cyclic displacement tests were performed on the full-scale reduced size RC frame infilled with prototype "SIM with closing gap" panel (2x2m; type 3; 227x113x80mm concrete units), Fig. 2a. Detailed results are reported in [3,13]. These tests identified three main response mechanisms for a frame with SIM infill panel: i) constant friction response, ii) Mohr-Coulomb response, and iii) plastic response. In-plane cyclic displacement tests were performed on the full-scale steel frame infilled with two different SIM panels: “with open gap” (type 1) and “without gap” (type 2) (both 2.4x2.4m made of 230x110x76mm concrete units), Fig 2b. These tests confirmed in-plane response mechanisms [14].

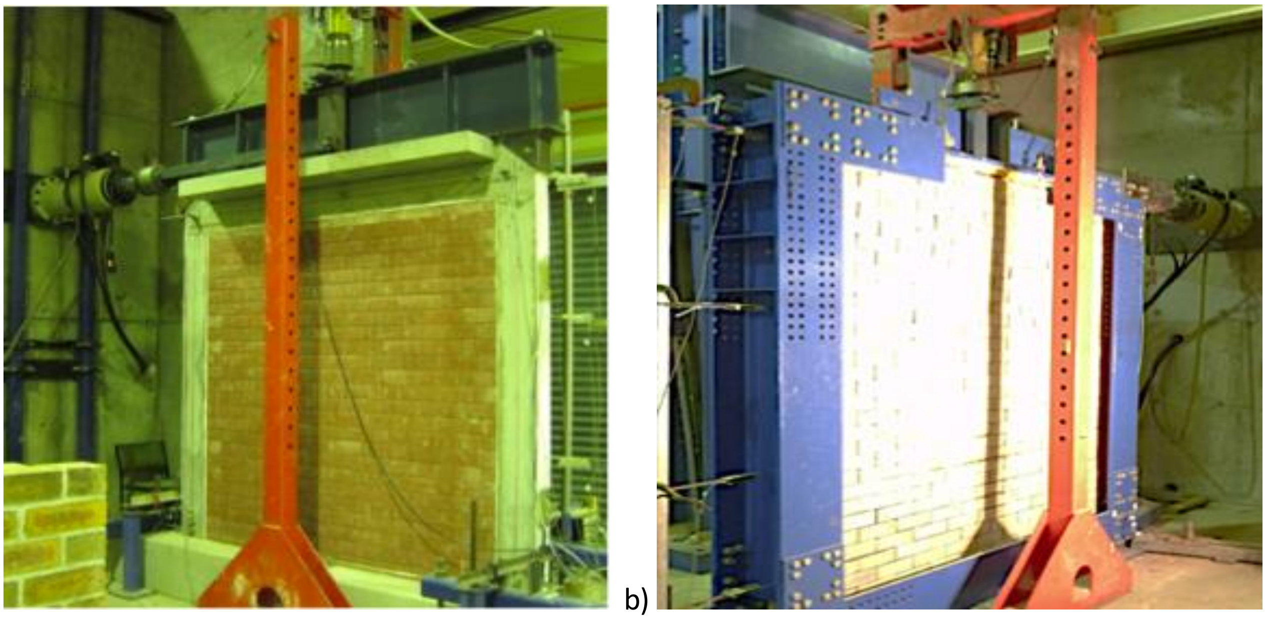
a)  b)

Fig. 2 – In-plane cyclic tests: a) on RC frame with panel of type 3; b) on steel frame with panel of type 1.

Numerical modelling of SIM panels was done using the microstructural approach of DIANA FE software [15] and the super-element approach [16]. Both models were verified using experimental results described above. SeismoStruct was selected for numerical simulations of multi storey frames’ behaviour as it is more practical program. Four FE models were created for three 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 infill panels.

The non-linear response due to monotonic load (pushover analysis) was simulated first. This simulation provided the yield displacement, the ultimate displacement, and the structural displacement ductility for all models. The second numerical simulation was the response history analysis under synthetic earthquake ground motion [17]. It confirmed that SIM panels are capable to improve seismic performance of multistorey frame buildings.

4. Evaluation of lateral in-plane force-displacement characteristic and energy dissipation in SIM panels

The equivalent static procedure provided in most earthquake design standards assumes ductile structural response and is not explicitly applicable to buildings with supplemental damping. Some guidelines on the testing and design of passive energy dissipation devices have been developed. A good example is the "FEMA 356 Prestandard and Commentary for the Seismic Rehabilitation of Buildings” [18]. According to this document, the force-displacement characteristics of an EDD shall be based on cyclic testing of prototype devices. This presents some difficulty in the case of SIM infill panels. Most other displacement-dependent EDDs have some form of diagonal (or cross) bracing and interact with the structural frame at certain points. They can be tested outside of the frame. A SIM infill panel is different; it interacts with the frame over the entire height of the columns and cannot be tested separately from the frame. FEMA 356 also states that the damping effect afforded by SIM panel could be calculated as follows:

$$\zeta_{ef} = \zeta_{frame} + \zeta^{*}_{SIM} = \zeta_{frame} + \frac{\Sigma U^{F}_{SIM}}{4\pi U^{S}_{frame}} \tag{4}$$

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, ΣU^{F}_{SIM} is the frictional energy dissipation in all SIM panels during one cycle of vibrations at designed target displacement, and U^{S}_{frame} is the maximum strain energy in the frame.

In the direct displacement based design procedure, 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^{F}_{SIM} during one cycle of vibrations for use in Eq. (4).

The frame and the masonry panel resist the lateral load jointly. Usually it is difficult to decouple individual force-displacement characteristics of these two structural elements at all levels of storey drift. If the storey drift is bellow the yield displacement of both these elements such decoupling is possible. However, the yield displacement for traditional masonry panels is very low and when it is reached traditional panels rapidly become unstable. When SIM panels are used, such decoupling is simpler because: i) since SIM panel is a mechanism, its yield displacement capacity is much greater than that of the frame structure and ii) frames with SIM panels also are more deformable and have greater yield displacement than frames with traditional masonry panels. Usually it is considerably greater than the target storey drift.

4.1 "SIM with open gap" (type 1)

The infilled frame assembly is represented as a combination of the structural frame and the mechanism, which consist of all frame elements connected by perfect pins with SIM panel inside (shown in Fig. 3).

The frame supports all vertical loads and some lateral loads. SIM panels resist only some lateral load by friction between bricks. The interaction between the frame and the panel occurs over the entire height of the pushing column. During the lateral distortion of the frame/SIM panel assembly sliding friction forces are induced on bead joints and depend on the weight of the panel above the joint, the friction coefficient, and the number of these friction surfaces. The greater the number of bead joints in the panel the more friction could be potentially induced in it. However, only sliding friction on slip surfaces is important for the lateral load resistance and the energy dissipation. In reality, sliding is a complex phenomenon. It does not occur simultaneously on every bead joint and/or on the entire area of every bead joint; some slip while others stick. Nevertheless, for simple evaluation of the in-plane load resistance of SIM panel type 1, a triangular distribution of frictional forces in the panel is assumed as shown in Fig. 3.

The friction is zero at the top of the panel and maximum at the bottom. The total frictional force depends on the weight of the panel as shown in Eq. (5), but independent of the number of bead joints.

$$\begin{gathered} F^{W} = \frac{F^{W}_{\max}}{l_1} \times \frac{H}{2} = \frac{W \mu H}{2 l_1}, \\ F^{W}_{\max} = H \times L \times t \times \rho \times g \times \mu \end{gathered} \tag{5}$$

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, μ is the coefficient of friction, l_1 is the unit length, and $F^{W}_{\max}$ is the maximum friction force in SIM panel.

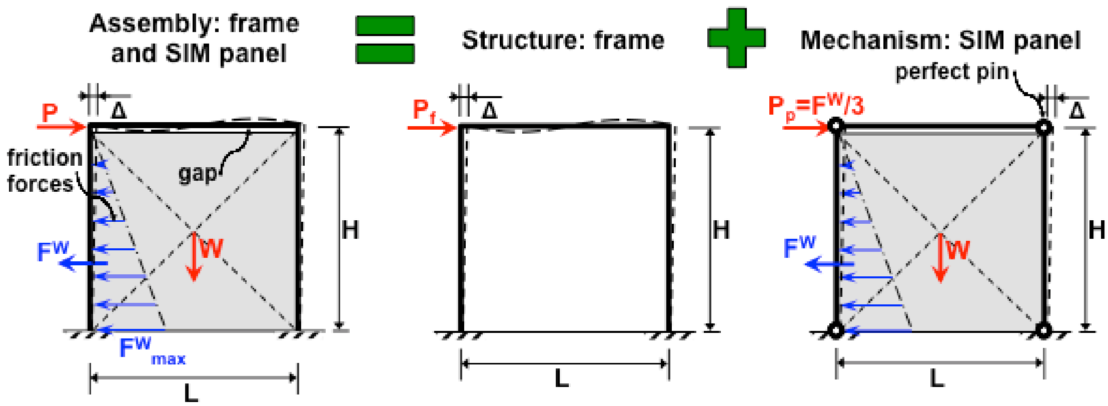


Fig. 3 – Decoupling of the lateral in-plane load resistance for SIM panel type 1.

The friction force on the *i*th bead joint, counting from the top, is:

$$F_i^W = F_{max}^W \frac{ih}{H}, \tag{6}$$

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

$$\delta_i = \Delta \frac{h}{H}. \tag{7}$$

In this case, the in-plane load resistance of SIM panel type 1 is not only linear but also is constant, see Eq. (8).

$$P_p = \frac{F^W}{3} = \frac{W \mu H}{6 l_1}. \tag{8}$$

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. 4, is:

$$U_i^F = 4A = 4F_i^W \delta_i \tag{9}$$

where, A is the shaded area in Fig. 4.

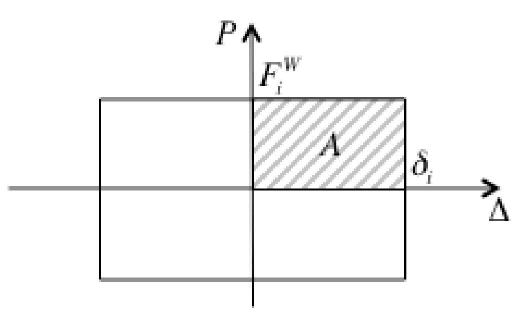


Fig. 4 - Force-displacement (P - Δ) diagram and frictional energy dissipation in the SIM panel type 1.

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:

$$U_{SIM}^{F} = \sum U_{i}^{F} = \sum_{i=1}^{H/h} 4F_{i}^{W}\delta_{i} = \sum_{i=1}^{H/h} 4F_{\max}^{W}\frac{ih}{H}\Delta_{t}\frac{h}{H} = 2F_{\max}^{W}\Delta_{t}\left(1+\frac{h}{H}\right). \tag{10}$$

4.2 "SIM without gap" (type 2)

In the case of SIM panel without gap, it is assumed that the load resistance consists of the constant friction component due to the weight of the panel (as for panels of type 1) and also the variable component due to additional friction forces on SIM bead joints caused by clamping of the weightless panel by the distorted frame, as shown in Eq. (11).

$$P_{p} = \frac{W\mu H}{6l_{1}} + \frac{F^{C}}{2}, \tag{11}$$

where, F^{C} is the frictional force due to clamping of the panel.

The interaction between the frame and the SIM panel must be considered to evaluate this variable component. The concept of a diagonal compression strut developed for traditional masonry panels is not applicable in this case for several reasons:

- There is no universally accepted theory of the compressive strut and all proposed methods are centred around the diagonal compressive strength of masonry panel, which is irrelevant for SIM panels;
- A SIM panel is not a diagonal bracing structure. When the frame sways the panel deforms accordingly with comparatively little lateral load resistance compared to traditional masonry panels;
- The frame-panel interaction differs from traditional not only in terms of the lateral load resistance but also in terms of distribution and nature of interactive forces. Unlike the traditional case, where interaction is assumed at the ends of the compression strut, a SIM panel interacts with the frame on the interface between it and the entire height of the pushing column.

The distortion of the frame's girder also causes some clamping of the SIM panel. It is assumed that this additional interaction occurs over the half of the girder length from the pushing column to the point of contra-flexure resulting in a formation of an eccentric clamping zone, as shown in Fig. 5.

The additional frictional forces due to the clamping of the panel depend on the vertical stress in the clamping zone, as shown in following Eqs. (12).

$$F^{C} = \sigma^{C}A^{C}\mu n; \qquad A^{C} = \frac{L}{2}t; \qquad n = \frac{H}{h}; \qquad \therefore\ F^{C} = \sigma^{C}\frac{L}{2}t\mu\frac{H}{h}, \tag{12}$$

where, σ^{C} is the vertical compressive stress in the clamping zone, A^{C} is the compressed area of a bead joint, and n is the total number of bead joints in the panel. The vertical stress in the clamping zone can be expressed in terms of the strain and then approximated in terms of the storey drift and the height for a realistically small distortion of the frame, as shown in Eqs. (13) below.

$$\begin{gathered}\sigma^{C} = E_{SIM}\varepsilon^{C}; \quad \varepsilon^{C} = \frac{s}{H}; \quad H \gg \Delta \gg s; \quad H^{2} = \Delta^{2} + (H-s)^{2} = \Delta^{2} + H^{2} - 2Hs + s^{2}; \\ s^{2} = \inf \approx 0; \quad s \approx \frac{\Delta^{2}}{2H}; \quad \therefore\ \sigma^{C} \approx E_{SIM}\frac{\Delta^{2}}{2H^{2}},\end{gathered} \tag{13}$$

where, E_{SIM} is the compressive modulus of elasticity for SIM, ε^{C} is the vertical compressive strain in the clamping zone, and s is the shortening of the clamped panel.

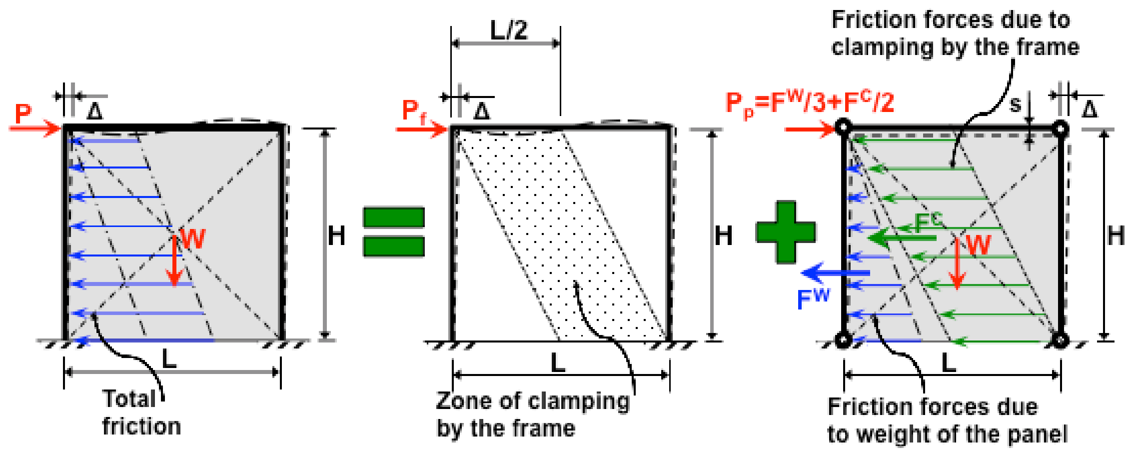


Fig. 5 – Decoupling of the lateral in-plane load resistance for SIM panel type 2.

Substitution of Eq. (13) into Eq. (12) transforms it into Eq. (14).

$$F^C \approx E_{SIM} \frac{\Delta^2}{2H^2} \frac{L}{2} t m \frac{H}{h} = \frac{E_{SIM} \Delta^2 L t m}{4Hh}. \tag{14}$$

The following Eq. (15) describes the lateral in-plane force-displacement characteristic of the SIM panel type 2.

$$\forall\ \Delta < \Delta_t : P_p = \frac{W m H}{6 l_1} + \frac{E_{SIM} \Delta^2 L t m}{8Hh}. \tag{15}$$

The frictional energy dissipation on the ith bead joint due to combined effect of self-weight of the panel above it and clamping by the frame, as shown in Fig. 6, is:

$$U_i^F = 4A_1 + 2A_2 = 4F_i^W \delta_i + 2\int_0^{\delta_i} F^C d\Delta = 4F_i^W \delta_i + 2\frac{F^C \delta_i}{3} \tag{16}$$

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 a 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:

$$U_{SIM}^F = \sum_{i=1}^{H/h} \left(4F_i^W \delta_i + 2\frac{F^C \delta_i}{3} \right) = \sum_{i=1}^{H/h} 4F_{\max}^W \frac{ih}{H} \Delta_t \frac{h}{H} + \sum_{i=1}^{H/h} \frac{E_{SIM} \Delta_t^2 L t m}{4Hh} \cdot \frac{2}{3} \Delta_t \frac{h}{H} = 2F_{\max}^W \Delta_t \left(1 + \frac{h}{H}\right) + \frac{E_{SIM} \Delta_t^3 L t m}{6Hh} \tag{17}$$

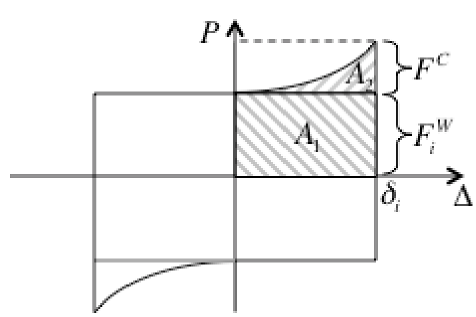


Fig. 6 - Force-displacement (P - Δ) diagram and frictional energy dissipation in the SIM panel type 2.

4.3 "SIM with closing gap" (type 3)

This type of SIM panel is the combination of types 1 and 2. When the gap is open the procedure for type 1 is applicable. When the gap closes, the procedure for type 2 should be used. This could be expressed using the singularity function, as shown in Eqs. 18.

$$\forall\, \Delta < \Delta_y : P_p = \frac{W\mu H}{6 l_1} + \frac{E_{SIM} \left\langle \Delta - \Delta_G \right\rangle^2 L t \mu}{8Hh}; \qquad \Delta_G = \frac{\left|\Delta_G^{left}\right| + \left|\Delta_G^{right}\right|}{2}, \tag{18}$$

where, Δ_y is the yield store drift for the frame, and Δ_G is the storey drift required for closing the gap between the top of SIM panel and frame. This equation is actually universal for all types of SIM panels and implies Eq. 8 and 15 for SIM panels of type 1 ($\Delta_G > \Delta$) and type 2 ($\Delta_G = 0$) correspondingly.

This type of SIM panel has, however, 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. 7. 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, it is necessary to replace the uneven gap with the equivalent even gap as shown in Eq. 18 and Fig. 7.

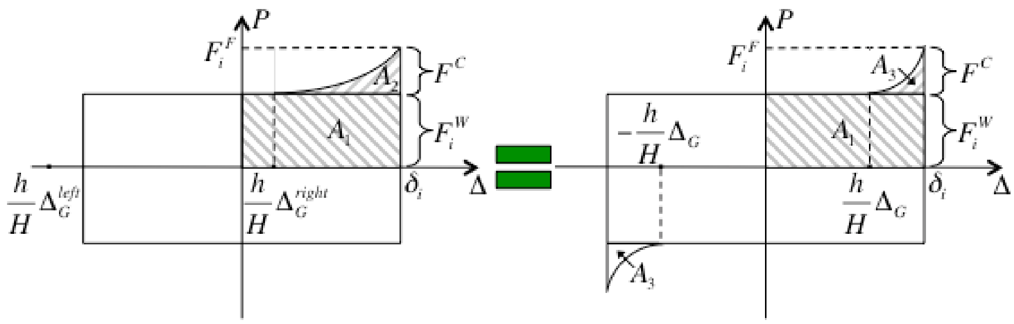


Fig. 7 - Force-displacement (P - Δ) diagram and frictional energy dissipation in the SIM panel type 3.

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. 7, is:

$$U_i^F = 4A_1 + A_2 = 4A_1 + 2A_3 = 4F_i^W \delta_i + 2\int_{\frac{h}{H}\Delta_G}^{\delta_i} F^C d\Delta = 4F_i^W \delta_i + 2\frac{F^C\left(\delta_i - \frac{h}{H}\Delta_G\right)}{3}. \tag{19}$$

The total frictional energy dissipation in a SIM panel with closing gap during one cycle of vibration at the target storey drift is:

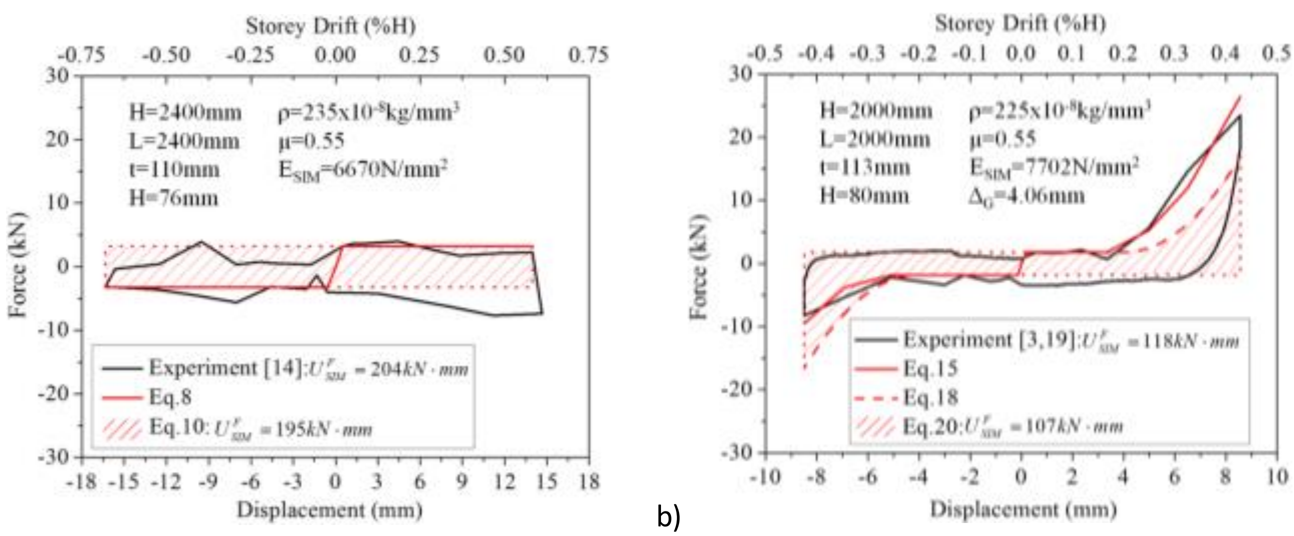
$$U_{SIM}^F = \sum_{i=1}^{H/h}\left(4F_i^W \delta_i + 2\frac{F^C\left(\delta_i - \frac{h}{H}\Delta_G\right)}{3}\right) = 2F_{\max}^W \Delta_t\left(1 + \frac{h}{H}\right) + \frac{E_{SIM}\left(\Delta_t - \Delta_G\right)^3 L t \mu}{6H^2}. \tag{20}$$

The total frictional energy dissipation in all SIM panels ΣU_{SIM}^{F} in a frame structure is the sum of individual contributions of each SIM panel calculated according to Eqs. (10), (17) and (20).

5. Examples of application

There are currently a limited number of experimental results for in-plane tests on frames with SIM infill panels. They are insufficient to comprehensively verify the proposed analytical procedure for evaluating of energy dissipation in SIM panels. The following examples aim to demonstrate how this procedure is compared to experimental results.

Two experimental studies were considered: steel frame with SIM panel of type 1 [14] and RC frame with SIM panel of type 3, which combines type 1 and type 2 behaviour [3, 19]. The presented procedure was used to evaluate the in-plane force-displacement characteristic (loading branches) of SIM panels at different levels of the storey drift and the energy dissipation. The experimental results are the envelope curves of the difference in the in-plane load resistance of the frame/panel assembly and the bare frame at the same levels of the storey drift. Fig. 8 shows the comparison of analytical and experimental results. They closely correlate for both case studies. However, while the calculated energy dissipation is close to the area within experimental envelope curves, it tends to overestimate the energy dissipation during individual cycles of vibration. This could be because Eqs. 10 and 20 do not account for the slip-stick effect on bead joints. This results in sliding friction forces induced not on the entire area of bead joints but only on a reduced area where bricks are sliding at each instance of time.



a) b)

Fig. 8 – Analytical and experimental force-displacement (P - Δ) diagrams for SIM panels: a) type1; b) type 3.

5. Conclusion

A procedure for evaluating the in-plane force-displacement characteristic and the corresponding energy dissipation for a new building system for masonry infill panels - semi interlocking masonry is presented. SIM is developed for earthquake resistant structures as a novel passive energy dissipation device. It dissipates earthquake energy through friction between dry stacked bricks. The presented procedure is analytical. It is based on physical principles and does not contain empirical constants.

The possible applications of this procedure include:

- Establishing the force-displacement characteristics of SIM panels without prototype tasting;
- Decoupling of individual characteristics of the frame and the panel from the traditional frame/panel assembly testing;
- Design of a new test for SIM panels within the pin connected mechanism as shown in Fig. 3;
- Estimation of the energy dissipation capacity of various SIM infill panels.

The procedure has been compared to experimental results. From this comparison it is possible to conclude that the proposed method reflects actual behaviour of SIM infill panels, is quite accurate, and that assumptions made in formulating this method are reasonable. However, the energy dissipation during individual cycles of vibration could be estimated with better accuracy if the procedure takes account of slip-stick effect on bead joints. This will be one of the future directions in SIM research when more experimental results will become available.

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