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Experimental Investigation of the Unreinforced Small Masonry Walls under Bidirectional Seismic Loading

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ABSTRACT

During an earthquake, a wall is subjected to a three-dimensional acceleration field and undergoes simultaneous in-plane and out-of-plane loading. It is often noted that in the field of brittle material strength, presence of one type of loading on a structural element affects the strength of that element against another type of loading. Considerable number of numerical and experimental studies, carried out to-date to investigate the behaviour of masonry walls under seismic loading, have either considered the in-plane response or the out-of-plane response of the wall separately without due consideration for any possible interaction between the two responses. In this paper, the results of a series of tests with different levels of simultaneous in-plane shear and out-of-plane bending actions on small brick walls constructed with standard high strength mortar are presented. The tests results indicate noticeable interaction between the in-plane shear and out-of-plane bending strengths of brick walls. The interaction curve appears to follow a circular trend.

Keywords:
Masonry; Brick wall; In-plane shear; Out-of-plane bending; Capacity interaction; Seismic response

1. Introduction

A brick wall undergoing an earthquake global acceleration field is subjected to both in-plane and out-of-plane loads; the former results from the storey shear force under horizontal loading, and the latter is either due to the out-of-plane inertia force caused by the considerable mass of the brick wall or the out-of-plane action of the floor on the wall. Considerable experimental, numerical and analytical studies are carried out on the behaviour of masonry buildings, particularly under earthquake loading; most carried out on the behaviour of brick walls.

As one of the earliest experimental works in this field, Thompson and Johnson [1] investigated the tensile strength of brickwork as the main parameter for brick wall in-plane failure and it's relation to the angle between the load and the direction of the bed joints. Another early work was done by Sinha and Hendry [2]. They carried out a series of tests on a number of brick walls with openings. They derived relations for the in-plane shear capacity of brick walls based on Mohr-Coulomb and maximum tensile strength criteria. Later, Abrams [3] reported on the results of a series of pushover and cyclic tests on unreinforced brick walls and suggested relations for calculating the in-plane shear and bending strengths of these elements. Tomazevic [4] also investigated diagonal shear strength of brick walls and compared the results with those obtained through relations suggested by Eurocode 6 [5]; showing some discrepancies in the results given by the latter. The in-plane shear behaviour of confined brick walls is also investigated experimentally by Tomazevic and Klemenk

[6], Tasnimi [7], Pourazin and Eshghi [8] and Riahi et al. [9], and simple load displacement models are suggested for these elements. In some of the latter studies, the effects of the confining concrete ring beam on the strength and behaviour of brick wall was also investigated. Other investigations have concentrated on the brick-mortar bond strength and response under in-plane direct shear force. Works carried out by Atkinson et al. [10], Elsakhawy et al. [11], Abdou et al. [12] and Maheri et al. [13] can be placed in this category. The effect of mortar joints on the in-plane shear strength of brick walls was also investigated by Maheri et al. [14], showing the considerable influence of the head joints on the response.

Many experimental and numerical investigations on masonry are aimed at deriving simplified analytical models for the response and capacities of this material. Although analytical methods have their own limitations, they are popular due to the simplicity. The majority of analytical methods have been presented for the in-plane shear response of masonry walls. Calderini et al. [15] reported on a series of existing analytical methods for calculating the in-plane strength of unreinforced masonry walls. In another research, Bojsilivic et al. [16] also reviewed the existing analytical methods for evaluating the in-plane strength of masonry walls and presented an approach for calculating the performance limit of masonry buildings. Roca [17] used simple equilibrium equations to calculate ultimate strength of solid brick walls and walls with openings under concentrated or distributed gravity and lateral loads. Giordano et al. [18] also presented a simple formula for predicting the in-plane strength of masonry portals based on the limit analysis approach. Benedetti and Steli [19] derived the lateral load-displacement curve for unreinforced and FRP reinforced masonry walls through analytical methods. They assumed an elastic-perfectly plastic behaviour for the masonry material.

Considerable experimental work is also reported for the strength and response of brick walls under out-of-plane loads. Kanit and Atimatay [20] carried out a cyclic test on an unreinforced brick wall and presented the failure mode and the hysteretic curve for the wall. Griffith et al. [21] also conducted a series of cyclic tests on full-scale brick walls with different aspect ratios and with or without openings. They subjected some of the specimens to pre-compression as well as the out-of-plane forces. Their results showed considerable post peak strength and displacement capacity in the walls resulting from the pre-compression. Derakhshan et al. [22] carried out static one-way, out-of-plane bending tests on three brick walls with different height to thickness ratios and various pre-compression loads. They obtained a three-line force-displacement model for walls in one-way bending. They concluded that pre-compression value and slenderness of the walls are important parameters in the out-of-plane response of the walls. Meisl et al. [23] carried out a series of out-of-plane shaking table tests on unreinforced brick walls with the same height to length ratios but constructed differently. The walls were subjected to three types of ground motions. Their results showed that the type of ground motion did not have significant effects on the out-of-plane strength of walls. In a recent experimental study, Maheri et al. [14] highlighted the orthotropic nature of the out-of-plane response of brick walls. The failure mechanism of the orthotropic wall panels undergoing bi-directional bending initiated with a vertical line crack as the stiffness of the wall in bending parallel to the bed joints far exceeded the stiffness of the wall in bending perpendicular to the bed joints. Following the softening of the wall parallel to the bed joint caused by the vertical crack, the wall followed a more isotropic behaviour and further cracks were in the classic diagonal form of isotropic failure [14].

Some researchers have also carried out the out-of-plane tests on masonry prisms. Tucker and Grimm [24] derived a relation between the out-of-plane strength of brick walls and flexural strength of masonry prisms. Rao et al. [25] and Pavia and Hanley [26], in similar experimental studies, investigated some parameters such as mortar type and moisture content of masonry units affecting the flexural strength of masonry prisms. They concluded that these parameters have significant effects on the flexural strength of masonry prisms. In addition, Khalaf [27] has proposed a new test set-up with less variation in results for obtaining the flexural brick-mortar cohesion.

In addition to the above experimental works, numerous numerical investigations have also been carried out in recent years to further study the individual responses of brick walls to in-plane and out-of-plane loading. A review of these studies is beyond the scope of this article. Good reviews can be found in [28-31].

Because of the multidirectional characteristic of the ground motion during an earthquake, the brick walls are simultaneously subjected to in-plane and out-of-plane loads. However, as reviewed above, the majority of studies on the behaviour of brick walls consider either the in-plane shear or the out-of-plane bending response. Very limited studies carried out on the response under simultaneous in-plane and out-of-plane loadings concentrate on the infill panels. Shapiro et al. [32] studied the interaction of the in-plane and out-of-plane responses in brick infills in concrete frames. They carried out a series of tests to investigate the effects of in-plane cracks on the out-of-plane strength of brick infills. Their test results showed that the in-plane cracks may reduce the out-of-plane strength of infills up to 100%. Another similar experimental study was carried out by Flanagan et al. [33] on brick infills in steel frames. Recently, Hashemi and Mosalam [34] have also studied the behaviour of concrete frames with infills under the combined effects of in-plane and out-of-plane loads. For this purpose, they conducted an in-plane shake table test on a concrete infilled frame. They subsequently used the test results to calibrate a numerical model which was further developed to include out-of-plane loading.

The absence of experimental investigations directly addressing the in-plane shear, out-of-plane bending capacity interaction in brick masonry in the literature is the main reason for the present study.

2. Experimental Program

A series of tests are conducted here on wallets to study the in-plane and out-of-plane capacity interaction and to determine the interaction curve for brick walls. Test specimens, set up, procedure and results follow.

2.1. Test Specimens

In total, twenty seven single-layer square brick wall panels were constructed for the experiments. All the panels were of the same size, material, workmanship and post-construction treatment so that the variation in their strengths would be reduced to a minimum. The wall panels for these tests were 60 cm by 60 cm and 10 cm thick. The brick units and mortar mixes used were compliant with internationally accepted norms for masonry construction. In constructing the panels, compressed brick units were used. These were the best type of engineered bricks available with low variation in quality and strength. Besides, the mortar was made of ordinary Portland cement and fine sand (passing sieve # 20) with a weight ratio of 1:3. The wall panels were cured under polythene sheet for 28 days against loss of moisture and for uniformity of treatment. Such treatment was shown previously by Maheri et al. [13-14] to result in considerable brick-mortar bond strength. It also ensured identical failure mechanisms for the panels. It should be noted that the brick-mortar bond strength and the mortar compressive strength are considerable, which may be different to those of the masonry commonly used in some countries such as Iran. A number of samples were also made for the material and prism tests. They include compressive and tensile tests on mortar, compressive and flexural tests on brick units, shear, compression and bending capacity tests of brickwork and determination of modulus of elasticity of mortar, brick units and brickwork. Selected properties are listed in Tables (1) and (2).

Table 1. Material properties of the brick and mortar.

Property	Brick (Lime-Sand)			Mortar (Cement-Sand)		
	Value	Standard	No. of Specimens	Value	Standard	No. of Specimens
Comp. Strength (MPa)	11	ASTM C67-11	5	34	ASTM C579-01	6
Flexural Tensile Strength (MPa)	2.0	ASTM C67-11	5	-	-	-
Direct Tensile Strength (MPa)	-	-	-	4.4	ASTM-C307-03	6
Young's Modulus (MPa)	7500	-	4	12000	ASTM-E111-04	3
Shear Bond Strength (MPa)	-	-	-	0.524	-	6
Water Absorption Rate (%)	17.5	ASTM C67-11	5	-	-	-

Table 2. Material properties of masonry prism.

Property	Value	Standard	No. of Specimens
Comp. Strength Normal to Bed Joints (MPa)	8	ASTM C1314-11a	5
Comp. Strength Parallel to Bed Joints (MPa)	4	-	5
Flexural Tensile Strength Normal to Bed Joints (MPa)	0.5	ASTM E518-10	5
Flexural Tensile Strength Parallel to Bed Joints (MPa)	3.0	-	3
Young's Modulus Normal to Bed Joints (MPa)	8000	ASTM C1314-11a	5
Young's Modulus Parallel to Bed Joints (MPa)	12000	-	5

2.2. Test Set-Up

Based on the observations made on the behaviour of walls during earthquakes and supported by experimental research reported in the literature, the most controlling in-plane shear failure mode in unreinforced brick walls is diagonal shear cracking. This failure mode is characterized with a diagonal crack perpendicular to the maximum tensile stress in the wall panel. There are a number of test set-ups in use for in-plane shear test on brick walls. Descriptions of different test set-ups are given by Vilet [35]. In the present study, the ASTM-519 [36] was utilised, regarding the size and preparation of the specimens, the test set-up and the procedure, to obtain the in-plane diagonal cracking strength of unreinforced brick walls. In this test, the brick wall panel is subjected to a static diagonal compressive force until failure. A number of researchers, including Calderini et al. [37], Gabor et al. [38], Brignolia et al. [39] and Borri et al. [40], have recently used this particular test to determine the in-plane shear strength of brick walls.

For the present study, a minor modification was, however, needed for the test set-up so that simultaneous application of the in-plane and out-of-plane loads to the wall panels could be carried out. To be able to subject the wall panels to the out-of-plane load, a reaction frame was necessary. This reaction frame needed to be designed and constructed in such a way that it did not confine the brick panel and also did not reduce the effective dimensions of the panel. For these purposes, a square steel frame having internal dimensions slightly smaller than the brick panel was positioned vertically on one face of the panel. To avoid local stress concentration at the interface between the rough surface of brickwork and the smooth surface of the steel frame, a thin layer of fast setting gypsum was applied at the interface.

The loading frame used for the tests was purposely manufactured to accommodate the test procedure. Figure (1) shows the loading frame. The in-plane diagonal compressive load and out-of-plane point load were applied to the panels using 300 kN capacity hydraulic jacks. The in-plane load was applied vertically on the vertical diagonal and the out-of-plane load was applied at the centre of the panel. Due to the relatively low out-of-plane strength of the brick panels, the out-of-plane load was exerted to the panel through a load ring at smaller load steps of 250 N. In each load step, panel displacements were measured with displacement transducers and recorded with a digital data logger. The test set-up regarding the positions of loading and the measuring sensors are shown in Figure (2). Three Contacting LVDTs were used to measure the displacements of the panels during loading; two transducers (S1 and S2), positioned on the horizontal diagonal, were to measure in-plane displacements on this diagonal and one transducer (S3), positioned at

Figure 1. Test set-up for simultaneous application of in-plane and out-of-plane loads.

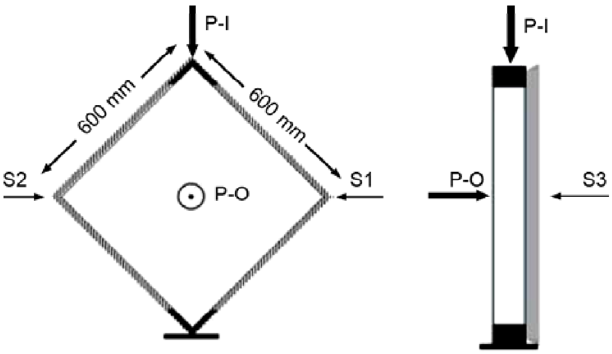


Figure 2. Position of loading jacks (P) and LVDT sensors (S).

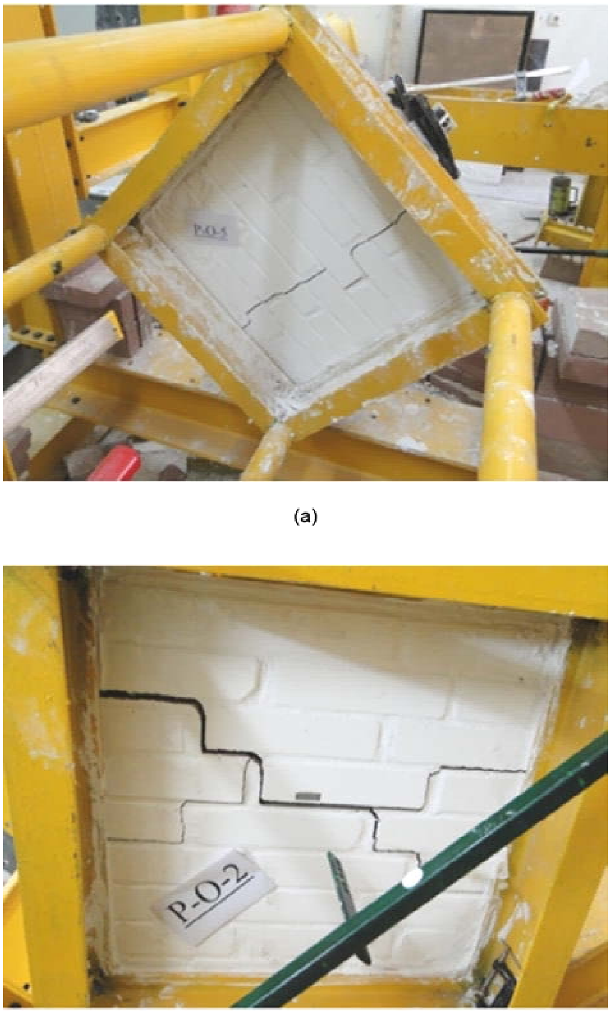
the centre of the panel directly opposite the central loading jack (P-O), was to measure the maximum out-of-plane displacement of the panel at that location.

2.3. Test Program and Results

The experimental program on the wall panels was conducted in three phases. In the first phase, the ultimate pure in-plane shear capacities of the wall panels were determined. For this purpose and to verify the repeatability of the tests, three panels were subjected to in-plane load (P-I) only and the results were compared. The mode of failure of all three panels was, expectedly, an explosive diagonal crack, Figure (3), and the difference in the ultimate strengths recorded for the three panels were very small (within 3%); indicating the uniformity of panel construction and performance. The average ultimate in-plane diagonal strength of the panels was measured as 48 kN.

Figure 3. Failure of the wall panels under in-plane shear load.

In the second phase, the behaviour and capacity of the wall panels to out-of-plane bending alone was investigated. For this purpose, three out-of-plane loading conditions were considered; (i) two-way bending, (ii) bending parallel to the bed joints, and (iii) bending perpendicular to the bed joints. The object of the two latter tests was to obtain the orthotropic tensile strengths of brickwork in perpendicular directions. In total, nine wall panels were tested in this phase; three for each bending condition to verify repeatability of the tests. Similar to the in-plane tests, the results of the repeated tests regarding both the mode of failure and the ultimate flexural capacity were very similar. In Figure (4), typical modes of failure of the brick panels under out-of-plane flexural tests are shown. The failure of the panels under two-way bending occurred in the form of two cross inclined lines at an ultimate point load equal to 11.75



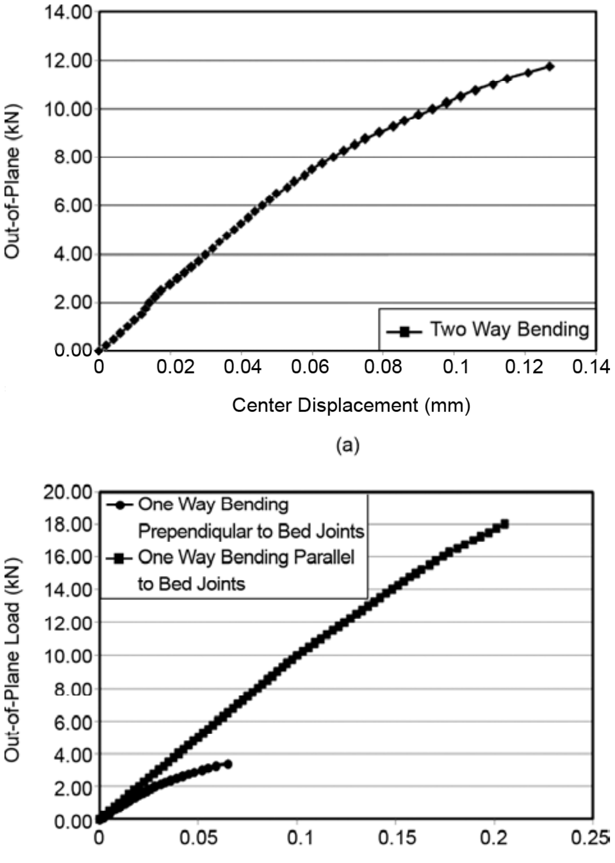
(a)

(b)

Figure 4. Typical out-of-plane tests of wall panels; (a) one way bending parallel to bed joints and (b) two-way bending.

kN. The failure of the panels in bending parallel to the bed joints was, expectedly, a single line crack along a bed joint, while the failure of panels in bending perpendicular to bed joints was a single line crack through bricks and head joints. The ultimate line loads applied to the two latter sets of specimens were 3.37 kN and 18 kN, respectively. Average load-displacement curves for the test panels are presented in Figure (5).

Following the above tests, the third and the main phase of the experimental program consisted of a series of tests on panels with different combinations of in-plane and out-of-plane loads. In each set of tests, the wall panel was first subjected to a certain value of out-of-plane load; then, while the out-of-plane load was kept constant, the in-plane diagonal compressive load was exerted stepwise to the panel and at each step displacements were recorded. The in-plane loading continued until failure. Each load combination was carried out on three panels for repeatability and their results averaged. The differences between the results obtained for the three panels in each load combination were small; indicating the consistency of the test panels. In total, five load combinations were thus tested. These load combinations corresponded to out-of-plane loads being, respectively, 33%, 50%, 67%, 83% and 90% of the ultimate flexural strength of the panels.



(a)

(b)

Figure 5. Average out-of-plane load-displacement curves; (a) two way bending, (b) one way bending.

The load-displacement curves for the test panels are presented in Figure (6). The results shown in this figure are average results for each load combination. It is evident that as the out-of-plane load increases, the in-plane shear capacity of the panel reduces. The shear stiffness of the brick panels is also reduced with increasing out-of-plane load.

The failure mechanism of the wall panels under combined in-plane and out-of-plane loads appears to be a combination of the in-plane diagonal shear and the out-of-plane bending failures discussed previously. The crack pattern of the panels subjected to low levels of out-of-plane loads follows a diagonal shape. With increasing out-of-plane load, bending cracks accompany the diagonal shear cracks at failure. A summary of the tests conducted and the test results is presented in Table (3).

As it was stated, the test results show reduction in the in-plane shear strength of brick wall panels in the presence of the out-of-plane load. This reduction appears more profound when the out-of-plane load nears the out-of-plane capacity of the panel. Similarly, the out-of-plane bending capacity is reduced in the presence of the in-plane shear loads. To gain a better insight into the in-plane shear and out-of-plane bending capacity interaction, the test results are plotted, in normalised form, in Figure (7). The in-plane, out-of-plane capacity interaction appears to almost follow a circular line.

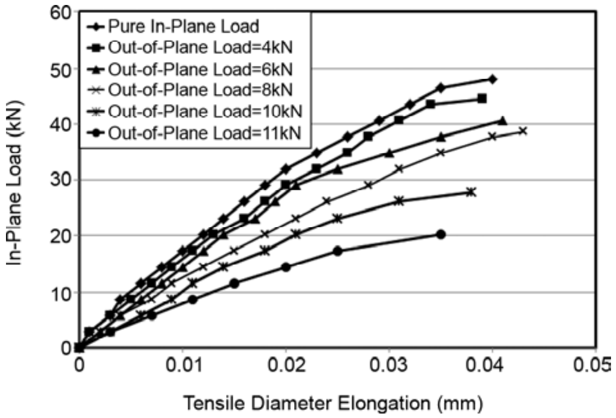


Figure 6. Average in-plane load-displacement curves for different in-plane, out-of-plane load combinations.

Table 3. A summary of the tests conducted and the test results.

	Type of Test	Description	Out-of-Plane Load (kN)	In-Plane Load (kN)
1	Pure in-plane test	Diagonal in-plane test	0.0	48.0
2	Pure two way out-of-plane test	The panel is subjected to a central point load in the out-of-plane direction	11.75	0.0
3	Pure one way out-of-plane test about an axis parallel to the head joints	The panel is subjected to a central line load parallel to the head joints	18.0	0.0
4	Pure one way out-of-plane test about an axis parallel to the bed joints	The panel is subjected to a central line load parallel to the bed joints	3.37	0.0
5	Test of panels subjected to simultaneous in-plane and out-of-plane loads	The panel is subjected to an out-of-plane point load equal to 33% of its pure out-of-plane capacity	3.92	44.0
6	Test of panels subjected to simultaneous in-plane and out-of-plane loads	The panel is subjected to an out-of-plane point load equal to 50% of its pure out-of-plane capacity	5.88	40.8
7	Test of panels subjected to simultaneous in-plane and out-of-plane loads	The panel is subjected to an out-of-plane point load equal to 66% of its pure out-of-plane capacity	7.83	38.4
8	Test of panels subjected to simultaneous in-plane and out-of-plane loads	The panel is subjected to an out-of-plane point load equal to 83% of its pure out-of-plane capacity	9.75	27.8
9	Test of panels subjected to simultaneous in-plane and out-of-plane loads	The panel is subjected to an out-of-plane point load equal to 92% of its pure out-of-plane capacity	10.81	20.15

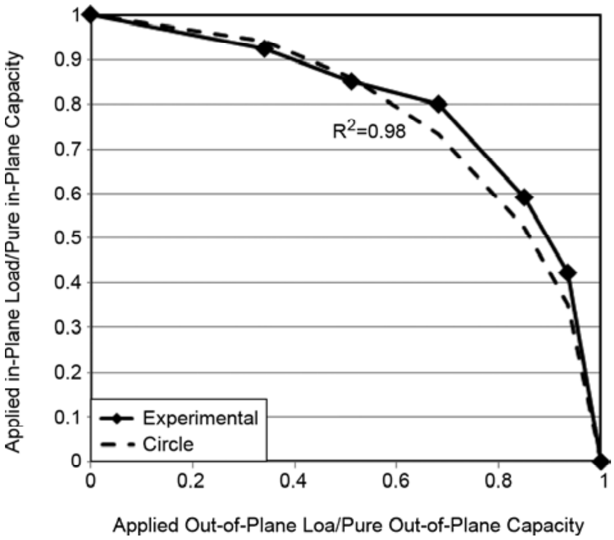


Figure 7. In-plane, out-of-plane capacity interaction curve for the wall panel.

4. Conclusions

The results of the investigations presented in this paper are summarised as follows;

- Noticeable interaction exists between the in-plane shear and out-of-plane bending capacities of brick walls. The interaction is particularly strong when one of the load types nears the wall's corresponding ultimate capacity. It is therefore recommended that this capacity interaction is taken into consideration when designing, undertaking vulnerability studies or retrofitting masonry buildings.
- The in-plane shear, out-of-plane bending capacity interaction curve appears to follow a circular form; a notion in need of further investigations.

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