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Deformation characteristics of brick masonry due to partial unloading

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Abstract. Experimental investigation into the behaviour of half-scale brick masonry panels were conducted under cyclic loading normal to the bed joint and parallel to the bed joint. For each cycle, full reloading was performed with the cycle peaks coinciding approximately with the envelope curve. Unloading, however, was carried out fully to zero stress level and partially to two different stress levels of 25 percent and 50 percent of peak stress. Stability point limit exhibits a unique stress-strain curve for full unloading but it could not be established for partial unloading. Common point limit was established for all unloading-reloading patterns considered, but its location depends on the stress level at which unloading is carried to. Common point curves were found to follow an exponential formula, while residual strains versus envelope strains can be expressed by a polynomial function of a single term. The relation between residual strain and envelope strain can be used to determine the stress level at which deterioration due to cyclic loading began.

Key words: partial unloading; reloading; residual strain; common point; stability point.

1. Introduction

Numerous studies have been conducted on the behaviour of brick masonry under monotonic loading conditions. The studies on brick masonry under cyclic loading were mostly in connection with seismic design of building with no particular emphasis on cyclic deformation characteristics of masonry assemblage (e.g. Chen *et al*. 1978, Macchi 1985 and Tomazevic *et al*. 1996). Only recently, the deformation characteristics of brick masonry under cyclic compressive loading were examined (Abrams *et al.* 1985 and Naraine and Sinha 1989). Karsan and Jirsa (1969) reported that plain concrete exhibits three fundamental stress-strain curves when subjected to cyclic loading. It has similarly been established that brick masonry panels possess three similar stress-strain curves under cyclic loading. These curves are termed envelope, common point and stability point stress-strain curves and they can all be expressed in mathematical forms (AlShebani and Sinha 1999). Cyclic actions may occur due to fluctuations of live load intensity, especially when the live load is the dominant gravity load. Therefore, an understanding of the response of brick masonry to cyclic

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compressive loading is particularly applicable to the design of structures having a large live load to dead load ratio. Repeated loading-unloading cycles can cause accumulation of residual strains which eventually produce failure. Abrams *et al.* (1985) proposed that accumulation of residual strain in the brick masonry assemblage due to load cycles can lead to a splitting failure of a brick unit at a compressive stress less than the failure stress under monotonically increased load. Full unloading-full reloading tests give an insight into the cyclic behaviour of brick masonry, but in practice it seldom occurs, rather it is a combination of partial and full unloading and reloading. Tests on plain concrete under random cycling revealed that partial unloading-reloading curves are significantly influenced by the residual strains accumulated and the envelope strain levels (Bahn and Hsu 1998). Tests on masonry under regular or random cyclic loading are vital for information related to material ductility, stiffness degradation, and energy dissipation characteristics.

This paper presents the results of compressive cyclic tests on half-scale sand plast brick masonry panels subjected to partial unloading. Analytical models for some of the features of the stress-strain hysteresis, namely, common point curves and residual strains are proposed.

2. Test specimen and instrumentation

Sand plast (a form of calcium silicate) brick masonry panels of dimension 360 mm × 360 mm × 115 mm have been constructed in stretcher bond from half brick units each measuring 110 mm × 55 mm × 35 mm. A mortar mix of 1 : 0.5 : 4 (cement : lime : sand) by volume was used for 5 mm thick bed joint. The water-cement ratio of the mortar was kept approximately to 0.95 by weight. The average compressive strength of the brick units was 23.4 N/mm^2 and the average compressive cube strength of mortar used for the joints at 28 days was 10.2 N/mm^2. Immediately after construction, the panels were put to sustain small weight of about 12 kg for twenty-four hours to ensure bond between brick units and mortar bed joints for the upper most courses. Specimens were cured under damp condition for 28 days before testing. X-Y plotters have been used to monitor the orthogonal displacements and the applied load through LVDTs and load cell respectively. The LVDTs are mounted on the two faces of the panel in two orthogonal directions. Prior trials of LVDTs positioning revealed that a gauge length of 250 mm is more consistent in depicting the displacements. The specimen and the LVDTs arrangements are shown in Fig. 1. Cyclic tests on

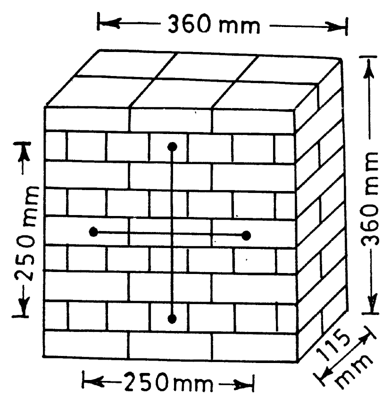

Fig. 1 Specimen dimension and LVDTs arrangement

half-scale brick panels and prototypes showed insignificant differences in behaviour for both loading conditions-normal and parallel to the bed joint (Naraine and Sinha 1989).

3. Test procedure

Cyclic loading is applied to the specimen using an Avery Universal Testing Machine of 1000 KN capacity. The load was uniformly distributed through steel box of 150 mm $\times$ 200 mm cross section. To minimize the effect of platen restraint and thus to ensure a more uniform state of stress in the model, 10 mm thick teflon sheets were inserted on the two bearing surfaces of the model.

Three types of tests were conducted on the test specimens.

(i) A monotonic test in which load is increased steadily until failure. This test establishes the monotonic stress-strain curve.

(ii) A cyclic test in which loading of each cycle is released when its peak approximately coincides with the envelope stress-strain curve. Reloading proceeds at the end of unloading to form new cycle. Therefore, unloading originated from the envelope curve and terminated at predetermined stress level at which the reloading for the next cycle started. For the ascending zone, reloading terminates by monitoring incremental increase in axial strain. For the descending zone, load was released when reloading curve tends to descend. This test establishes the common point stress-strain curve.

(iii) A cyclic test in which reloading and unloading is repeated several times for each cycle. Unloading is done when reloading crosses the previous unloading curve. The process is repeated until both unloading and reloading paths are stabilized i.e., the unloading-reloading intersection point is stabilized at a lower bound point. This test establishes the stability point stress-strain curve.

4. Failure mode

Failure mode of sand plast masonry due to partial unloading and due to full unloading follow a similar pattern. In general, the failure mode is dependent on the orientation of bed joints. For specimens loaded normal to the bed joint, failure is usually the combination of splitting in brick units, and splitting in head joint and slipping of bed joint. For specimens loaded parallel to bed joint, failure occurs by thorough cracks along the full length of the vertical bed joint and subsequently disintegration of brick units along the course line.

The mean failure stress for specimens loaded normal to bed joint for partial and full unloading was 8.9 N/mm^2 and 9.5 N/mm^2 respectively. The corresponding values for specimens loaded parallel to bed joint for partial and full unloading was 7.8 mm^2 and 8.2 N/mm^2 respectively. Therefore, the ratio between the mean orthogonal strength is approximately 0.88 for partial unloading and 0.86 for full unloading.

5. Stress-strain hysteresis

The brick panels have been tested cyclically in uniaxial compression normal and parallel to the

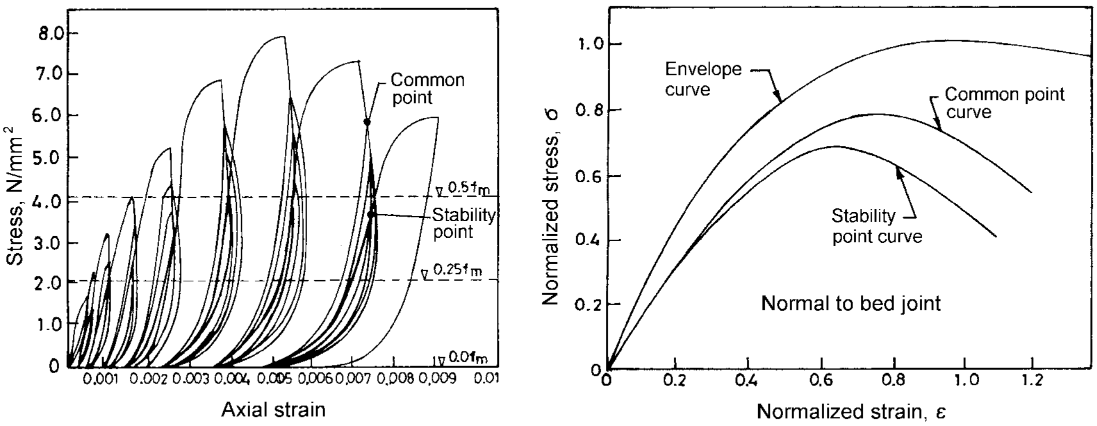

Fig. 2 (a) Typical stress-strain hysteresis for full unloading-reloading, (b) Typical analytical stress-strain curves for full unloading-reloading

bed joint until failure. The application of cyclic loading may produce three distinct stress-strain curves. The envelope curve can be obtained by superimposing the cycle peaks on the monotonic stress-strain curve. The cycle peaks represent the stress-strain peaks of common point test and stability point test. The common point curve represents the locus of intersection points of unloading-reloading paths. Cycling above the common point results in an increase in strain accumulation, while cycling below the common point leads to closed stress-strain loops. If unloading-reloading is repeated several times for each cycle, other loci of common points are formed and stabilized at a lower bound termed as the stability point curve. Envelope, common point and stability point curves are therefore constitute the main features of the cyclic stress-strain hysteresis. Typical stress-strain hysteresis for full unloading-reloading is shown in Fig. 2(a). The envelope curve was established by superimposing the stress-strain peaks of cyclic test types (ii) and (iii) on the monotonic stress-strain curve. The stress coordinate was normalised with respect to peak (failure) stress of each specimen and the strain coordinate was normalised with respect to strain when peak stress is attained. The coordinate of envelope peak point is therefore (1,1). The normalised stress-strain envelope curve was found to follow an exponential formula (AlShebani and Sinha 1999). The parameters of this formula, however, were found to depend on the loading direction being normal or parallel to bed joint.

6. Partial unloading

Full reloading refers to the peak of reloading curve coinciding with envelope curve and full unloading refers to the unloading curve terminating at zero stress level. Tests on masonry under repeated full unloading-full reloading allow convenient examination of its cyclic deformation characteristic, but in reality, full unloading-full reloading seldom occurs. In practice, masonry under cyclic loading is usually subjected to combinations of full and partial unloading-reloading cycles. Cyclic stress-strain characteristics due to full unloading-reloading have been reported elsewhere (AlShebani and Sinha 1999) and the analytical curves are shown in Fig. 2(b). The test results reported here are concerned with masonry cyclic behaviour due to partial unloading. For each loading curve, full reloading was performed up to the envelope curve, while unloading was carried out to predetermined stress levels for each loading direction. The three stress levels at which unloading was terminated were taken as zero stress level (full unloading), 0.25 f_m and 0.50 f_m stress levels (partial unloading), where f_m is the failure stress. Since the two unloading stress levels of 0.25 f_m and 0.50 f_m were predetermined based on anticipated failure stress, the ratio of unloading stress to failure stress may not be exactly 0.25 and 0.50 respectively. It has been observed that the maximum deviation was considered insignificant to the unloading stress ratio. A total of 30 specimens were tested for the two loading conditions. Typical common point tests for partial unloading are shown in Fig. 3 for loading normal to bed joint and in Fig. 4 for loading parallel to bed joint. The resulted common point curves and stability point curves due to partial unloadings and the residual strains with respect to envelope strains are examined in the next sections.

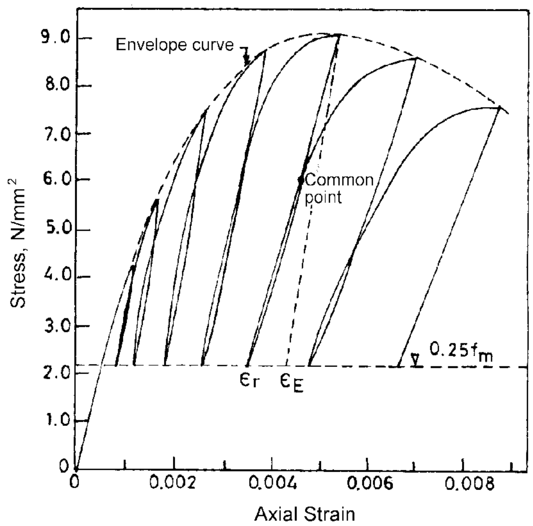

Fig. 3 Common point test for partial unloading: Normal to bed joint

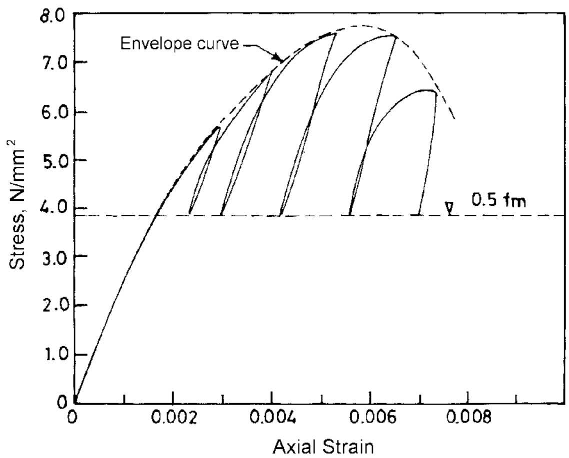

Fig. 4 Common point test for partial unloading: Parallel to bed joint

6.1 Common point curves

The common point curves due to unloading to zero stress level (full unloading) were found to follow an exponential formula (AlShebani and Sinha 1999), which can be written as follows:

$$\sigma = \varepsilon^{\beta} \mathrm{Exp}\left[\left(1 - \frac{\varepsilon}{\alpha}\right) \cdot \varepsilon\right] \quad (1)$$

where, σ and ε are the non-dimensional stress and strain. The experimental results are plotted in a non-dimensional coordinates, where stress is normalized with respect to failure (peak) stress and strain is normalized with respect to strain corresponding to peak stress. The parameters α and β are constants determined from test results and using statistical analysis that maximise the correlation index. While α accounts for the change in strain at peak stress, β is regarded as a shape factor. For loading normal to bed joint, the values of α and β are equal to 0.73 and 0.80 respectively. The corresponding values for loading parallel to bed joint are 0.70 and 0.73.

The common point curves for the other two unloading stress levels follow a similar trend. It is, therefore, proposed that Eq. (1) can represent common point curves for partial unloading provided that the parameters α and/or β are modified. Thus, it is suggested that for the range of unloading stress levels considered, the parameter α is taken to be constant and equal to 0.73 for loading normal to bed joint while β is expressed as follows:

$$\beta = 0.80(1 - 0.3\sigma_{ul}) \quad (2)$$

For loading parallel to bed joint, both α and β are functions of the unloading stress levels which are expressed as follows:

$$\alpha = 0.70\ (1 - 0.11\ \sigma_{ul}) \quad (3)$$

$$\beta = \alpha + 0.03 \quad (4)$$

Where, σ_{ul} is the ratio of unloading stress level to failure stress level.

The non-dimensional common point curves for the three unloading stress levels are plotted in Fig. 5 and in Fig. 6 for the two loading directions. The curves represent the average values of test data

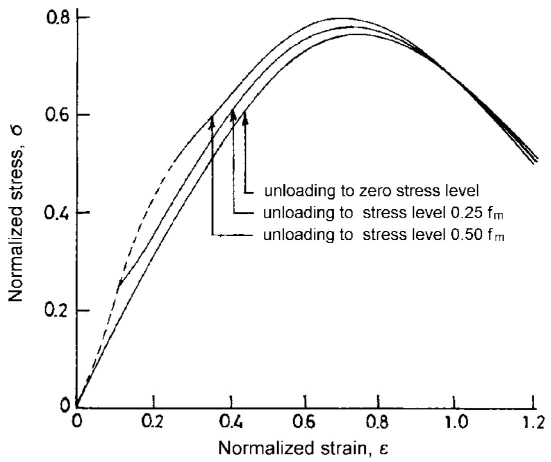

Fig. 5 Common point curves normal to bed joint

with correlation index, i_c ranging from 0.88 to 0.94, an indicative of reasonable agreement.

It has been observed that for the range of the test data considered in this investigation, common point curve depends on the stress level at which unloading terminates. It has been further observed that the influence of the unloading stress level on the locus of common point is more pronounced in the pre-peak zone for load normal to bed joint and in the post-peak zone for load parallel to bed joint. This may be due to the difference in the rate of accumulation of plastic strain under the two loading directions. It has been stipulated that when specimens are loaded parallel to bed joint, the growth of cracks through vertical bed joint would lead to the formation of brickwork columns (AlShebani and Sinha 1998). Upon reloading, the locus of common points of these columns seem to descend as unloading stress levels increase.

6.2 Stability point curves

The authors (1999) have considered that the stability point curve can be regarded as the permissible stress level limit for sand plast brick masonry under cyclic loading. They have further proposed that for unloading to zero stress level, the stability point curve follows Eq. (1) with parameters α and β equal to 0.58 and 0.80 respectively for loading normal to bed joint and 0.54 and 0.73 respectively for loading parallel to bed joint. When unloading is carried out to stress level ratio of 0.25, the locus of stability points is not unique as it fluctuates. When unloading is carried out to stress level ratio of 0.50, the locus of stability point cannot be established as repeated reloading-unloading of any cycle fails to establish descending reloading-unloading intersection points. In this case, repeated reloading-unloading for the same cycle does not fall within the loop of the original reloading-unloading of that cycle. The observation for stability points due to partial unloading to stress level ratio of 0.25 and the stability point curve due to unloading to zero stress level are shown in Fig. 7 and in Fig. 8 for the two loading directions.

6.3 Residual strains

As the peak stress of cyclic loading increases, the residual (plastic) strains accumulate and

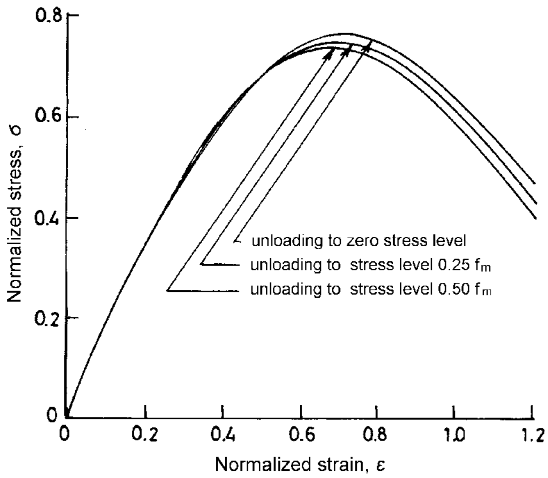

Fig. 6 Common point curves parallel to bed joint

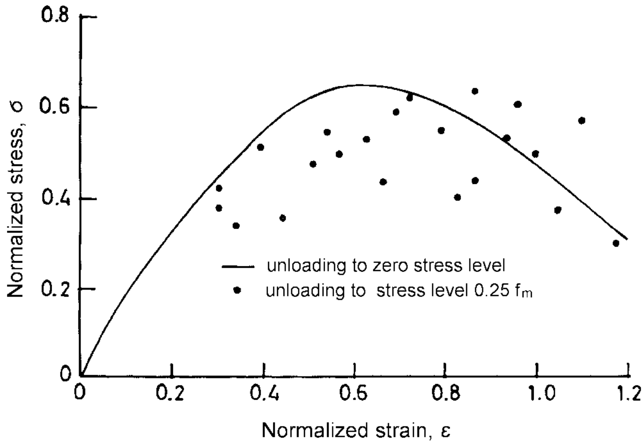

Fig. 7 Stability point curves normal to bed joint

Fig. 8 Stability point curves parallel to bed joint

eventually lead to failure. The accumulation of residual strains is usually regarded as a damage indicator of brick masonry under cyclic loading. Based on the test data, the relation between residual strain, ε_r and the envelope strain ε_E at any given load cycle can be expressed in the following general form:

$$\varepsilon_r = C_p(\varepsilon_E)^{n_p} \tag{5}$$

Where, values for the constant C_p and the power terms n_p are dependent on the loading direction, unloading stress level and the stage of cyclic loading. Values for ε_r and ε_E are the normalised residual and envelope strains with respect to strain corresponding to peak stress. Except for unloading to zero stress level, the values of constant C_p and the power term n_p change at a certain envelope strain level, ε_l. The values of ε_l, C_p, n_p and the correlation index i_c are shown in Table 1. The values of i_c suggest reasonable correspondence between the proposed formula (Eq. 5) and the experimental data.

The variation of residual strains with envelope strain are shown in Figs. 9 and 10 for the two loading directions. It has been observed that the rate of residual strain accumulation is relatively

Table 1 Values for ε_l, C_p, n_p and i_c

Equation constants	Unloading stress ratio normal to bed joint					Unloading stress ratio parallel to bed joint				
	0.0	0.25		0.50		0.0	0.25		0.50	
ε_l		<0.40	≥0.40	<0.40	≥0.40		<0.50	≥0.50	<0.60	≥0.60
C_p	0.47	0.50	0.65	0.74	0.78	0.35	0.27	0.55	0.46	0.81
n_p	1.20	0.70	0.95	0.83	0.95	2.0	0.45	1.50	0.40	1.50
i_c	0.94	0.91		0.8		0.93	0.90		0.87	

slower at early loading stage for loads parallel to bed joint than for loads normal to bed joint. This may explain that the three common point curves follow close paths at early stage of the ascending zone for load parallel to bed joint as opposed to the behaviour when loads are normal to bed joints. It can also be stipulated that the values of ε_l at which values of constants of Eq. (5) changes may represent the beginning of the process of strength deterioration of the specimen. For loading normal to bed joint, the corresponding stress for ε_l is approximately the same regardless of unloading stress level. The stress level at which the process of deterioration began is about two-thirds of failure

Fig. 9 Variation of residual strain with envelope strain normal to bed joint

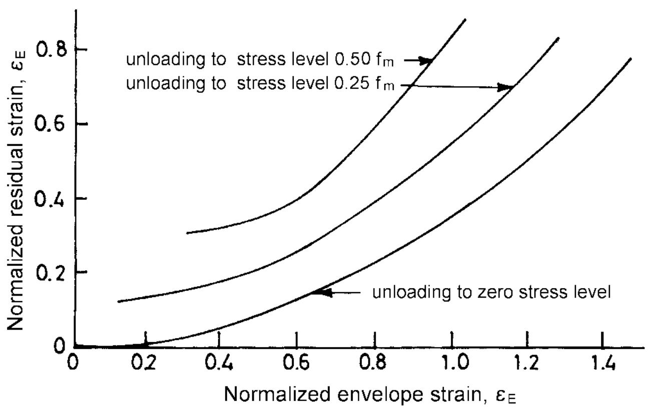

Fig. 10 Variation of residual strain with envelope strain parallel to bed joint

(peak) stress for loading normal to bed joint. For loading parallel to bed joint, the process of deterioration starts at about two-thirds of failure (peak) stress when unloading to zero stress level but increases with the increase of unloading stress level. It was therefore observed that for unloading to 0.25 f_m, the stress corresponding to ε_l is about 0.73 f_m and for unloading to 0.50 f_m, the stress corresponding to ε_l is about 0.83 f_m.

7. Conclusions

Experimental investigation on sand plast brick masonry subjected to cyclic loading reveals that the common point curve depends on the stress level at which unloading terminates. Stability point curve cannot be established for partial unloading up to stress ratio of 0.25 but it exhibits a unique stress-strain curve for full unloading. The common point curve and the stability point curve can be expressed mathematically by exponential formula based on the best correspondence with experimental data which is measured by the correlation index. The relation between the residual strain and the envelope strain can be expressed by a general polynomial function of one term. The analytical curves of residual strain versus envelope strain indicate the points at which the strength deteriorations of the specimen occurs. The stress at which strength deteriorations begin is approximately the same for the unloading stress levels considered when load is normal to bed joint. However, this stress increased with the increase in unloading stress level when load is parallel to bed joint. At an early loading stage, the accummulation rate of residual strain is relatively slower for loading parallel to the bed joints and that may explain the closely followed paths of the three common point curves in the ascending zone for this loading case as opposed to their counterparts for loading normal to the bed joints. The finding of this investigation suggests a more thorough examination of the behaviour of brick masonry under more random compressive cycling is needed.

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