# RESPONSE OF CLAY-UNIT MASONRY TO REPEATED COMPRESSIVE FORCES

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ABSTRACT Behavior of clay-unit masonry was found to be influenced significantly by repeated compressive forces. A total of 120 stack-bond test prisms were subjected to concentric axial forces. Amounts of sustained and alternating stress were varied as well as the mortar type. Results showed that reductions in static strengths as large as 30% were possible for as little as 40 cycles of loading at a relatively small amplitude of alternating force. Strength reductions were attributed to inelastic straining of mortar and accumulation of lateral tractions between mortar and brick. Specimens with stronger mortar were more sensitive to repeated loadings than those with weaker mortar.

## 1. INTRODUCTION

Response of masonry structures to dynamic loadings such as winds or earthquakes is difficult to describe analytically because resistance mechanisms are not fully understood. One basic uncertainty is how the material behaves when subjected to a repeated force. An experimental study is described herein which examined behavior of stack-bond test prisms that were subjected to compressive forces that either increased monotonically to failure or were alternated about a constant level of sustained force. Parameters of the study were the mortar type and the relative amounts of sustained and alternating force.

## 2. BACKGROUND

Tests of one-story masonry wall panels subjected to repeated and reversed in-plane lateral loads (1,2,3) indicated that reductions in strength and stiffness were possible with successive cycles of loading. Very little research has been done, however, on behavior at the material level for masonry under repeated stress. A sizable amount of research, however, has been done on this topic for plain concrete. Much of this work has been summarized by Hsu (4) and RILEM Committee 36-RDL (5).

A previous study by McNary (6) examined the basic mechanics of clay-unit masonry under monotonically increasing compressive forces. The experimental study determined stress-strain relations for mortar and brick coupons subjected to multiaxial states of stress. A mathematical model proposed by Atkinson (7) was used to relate strains of the constituent materials and

determine loading-deflection relations for a stack-bond prism. Through comparison of calculated and measured results, a theory for the mechanics of clay-unit masonry in compression was formulated.

Results of McNary's study showed that behavior of masonry under compressive stress is dependent primarily on the dilatant properties of the mortar. In masonry under compression, lateral stresses are developed in the brick and mortar in addition to compressive stress. Basically, the brick tends to confine the mortar thus inducing lateral compressive stress in the mortar. Conversely, the lateral expansion of the mortar induces lateral tensile stress in the bricks. Inelastic properties of mortar cause a much greater development of lateral tensile stress in brick than would mortar with linear elastic properties. Thus the confinement by the bricks causes an increase in vertical load capacity of mortar and lateral expansion of the mortar causes a decrease in vertical load capacity of brick.

3.0 PROPOSED THEORY FOR REPEATED FORCES

Results of the past study may be extrapolated to suggest behavioral traits under a repeated compression. If residual tractions are developed for a single load cycle, then an accumulation of these tractions would be possible for several cycles. If bond between brick and mortar is not broken, a splitting failure of a brick unit could occur at a prism compressive stress less than the prism failure stress under a monotonically increasing force.

According to this proposed theory, compressive strength of a prism would be related to the parameters that cause inelastic strains in mortar. Three such parameters would be (a) the maximum compressive stress, (b) the magnitude of alternating stress, and (c) the number of loading cycles at a particular amplitude of stress.

To help evaluate the proposed theory, brick and mortar specimens were subjected to uniaxial repeated compression. Although these stress states may have been simplistic, the tests did reveal that the brick (Fig. 1) behaved nearly elastically, and the mortar (Fig. 2) behaved inelastically for large-amplitude cycles. Residual mortar strains

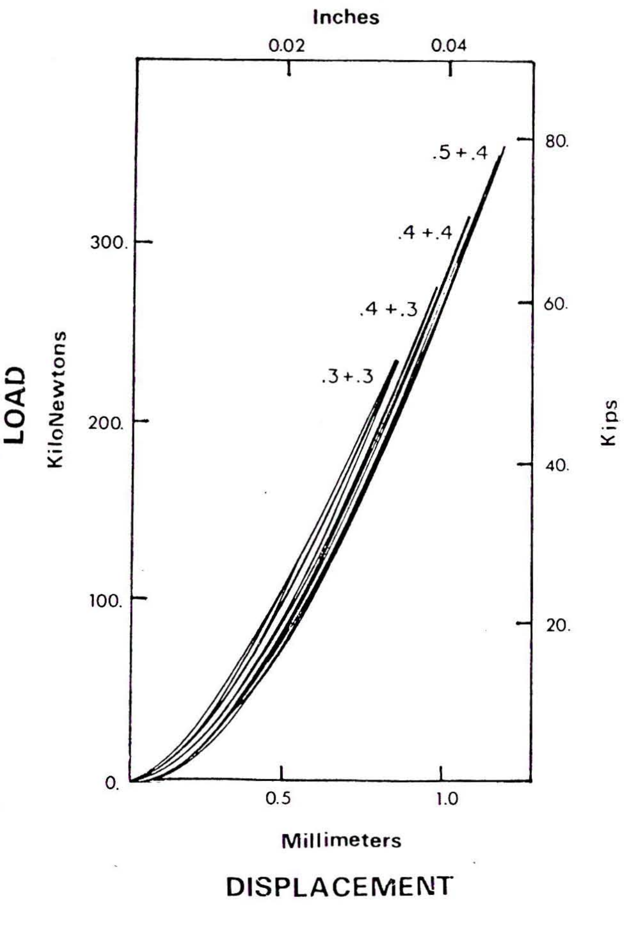


Fig. 1 Behavior of Brick

were observed for each inelastic cycle in a geometric pattern that attenuated for early cycles and increased in later cycles near failure.

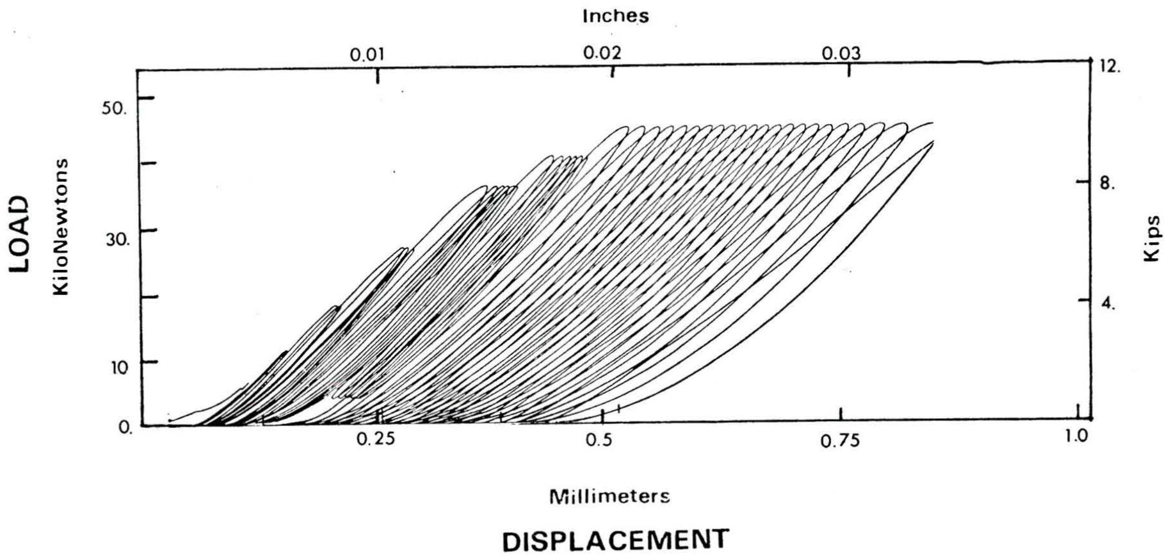


Fig. 2 Behavior of Type S Mortar

It is also possible that splitting strength of a fired clay brick may deteriorate with repeated lateral tensile stress. Cracks originating from microfissures may propagate progressively with each cycle, and thus decrease the resistance to splitting. The crack propagation may be hindered because of effects related to strain rate, however.

Behavior of a stack-bond prism under repeated stress is likely a complicated interaction of these two phenomena. Inelasticity in the mortar may influence the crack propagation in the brick, and correspondingly, progressive crack propagation within the brick may influence the internal stresses and confinement of the mortar. The intent of the experimental investigation described in this paper was to study the interaction of these two phenomena.

## 4. OBJECT AND SCOPE OF STUDY

The object of the study was to investigate the mechanics of masonry prisms in resisting repeated compressive stress.

A total of 120 geometrically identical prisms were fabricated using four different types of mortar and one kind of brick. Approximately one-half of the prisms were loaded monotonically to establish an average ultimate static strength for prisms of each mortar type. The remaining prisms were tested under various combinations of alternating compressive stress about a mean or sustained compressive stress; both values were identified as percentages of the average ultimate static compressive stress.

## 5. TESTING PROGRAM

### 5.1 Specimen Description

Experimental specimens were obtained from stack-bond prisms (Fig. 3) which consisted of five clay bricks bonded with mortar. The prisms were fabricated in the laboratory using a steel alignment jig which insured essentially parallel units and a constant thickness of mortar joint. After air drying for one day, the prisms were placed in a fog room for five days and then removed to air dry for one more day prior to capping and testing. Full prisms were cut in half (Fig. 4) to provide sibling specimens of hypothetically the same strengths, however, variations in strengths of the halves were in many cases more than that for uncorrelated specimens.

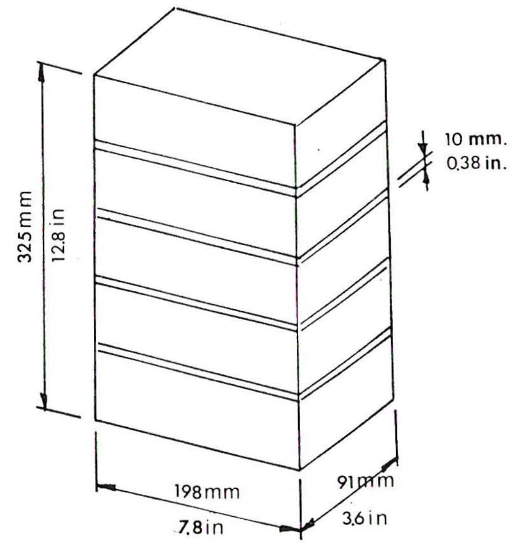


Fig. 3 Test Prism

Fig. 4 Sibling Specimens

A hydrostone cap 1.2 mm thick (0.05 inch) was used on both ends of the specimen. Greased teflon sheets were used to reduce friction between compressive platens and the test specimens.

### 5.2 Materials

Masonry units were underburned solid clay bricks which were extruded and fired. Samples were tested in flatwise compression in accordance with ASTM Standard C67. The brick unit had an average compressive strength of 78.6 MPa (11.4 ksi) with a coefficient of variation of 16% for the six samples tested.

Water content of mortar was evaluated by checking flow with that of a material of standard viscosity (ASTM Method No. C230-68). Water-to-cement ratios and relative amounts of sand, cement and lime for each mortar type are listed in Table 1. A single batch

of mortar was sufficient to build two full prisms. Cube samples were made for each batch of mortar. Mortar strength data is presented in Table 1.

Table 1 - Mortar Properties

| MORTAR TYPE | PROPORTIONS OF CEMENT:LIME:SAND | W/C RATIO | NUMBER OF SPECIMENS | COMPRESSIVE STRENGTH (psi) | (MPa) | COEFFICIENT OF VARIATION |
|---|---|---|---|---|---|---|
| M | 1:1/4:3 | .546 | 18 | 5070 | 36.0 | 7.8% |
| S | 1:1/2:4-1/2 | .847 | 21 | 2638 | 18.2 | 4.9% |
| N | 1:1:6 | 1.190 | 6 | 1265 | 8.7 | 5.4% |
| O | 1:2:9 | 1.976 | 21 | 396 | 2.7 | 12.1% |

### 5.3 Loading Patterns

A servohydraulic load frame with a capacity of 500 kN (110 kip) was used to load the specimens. Loads that increased to failure monotonically were applied in accordance with a constant piston velocity equal to 0.1 mm/sec (0.005 inch/sec). The cyclic forces were applied with respect to a prescribed sinusoidal pattern which was centered about a constant level of sustained force. The cycle forces were applied at a frequency of 0.1 cycles per second which was considered slow enough so that strain-rate effects would be minimal.

Prescribed values of sustained and alternating forces were quantified from the average of static ultimate strengths of a set of counterpart specimens. Sustained forces ranged from 20% to 70% of ultimate static strengths. Alternating forces ranged from 10% to 40% of static strengths. The number of loading cycles was limited to 180 cycles. Specimens which did not fail at 180 cycles were subsequently loaded monotonically to failure.

## 6.0 TEST RESULTS

### 6.1 Behavior Under Monotonically Increasing Compression

Typical load-deflection curves for test prisms fabricated of Types O and S mortar are shown in Fig. 5. Stiffness and strength of a prism were related to the mortar type. Deformations were linear with loads up to a limit which was dependent on the mortar strength. Failure of specimens with the stronger mortar were explosive at maximum loads. Specimens with the weaker mortar revealed a softening behavior in the post-peak region.

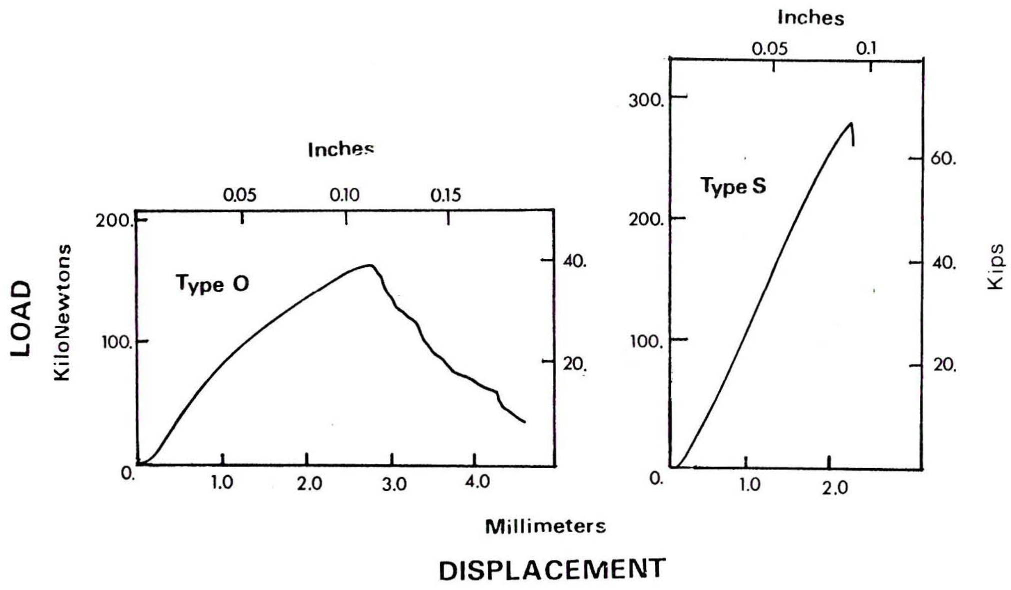


Fig. 5 Behavior of Test Prisms Under Increasing Force

Stresses and strains at maximum compressive force for specimens subjected to monotonic loading are listed in Table 2. As should be expected, average ultimate compressive stress increased with mortar strength. It is interesting to note, however, that the coefficient of variation of stress values also increased with mortar strength.

Table 2 Measured Ultimate Stresses of Test Prisms Under Monotonically Increasing Force

| Mortar Type | Apparent Stress (ksi) | (MPa) | Average Stress with % cov | Apparent Strain | Average Strain with % cov |
|---|---|---|---|---|---|
| S | 4.85 | 33.44 | | 0.0067 | |
| | 3.82 | 26.33 | | 0.0063 | |
| | 4.87 | 33.58 | | 0.0060 | |
| | 4.67 | 32.20 | | 0.0055 | |
| | 4.03 | 27.79 | 4.46 ksi | 0.0050 | 0.0059 |
| | 4.08 | 28.13 | 30.75 MPa | 0.0051 | 11.0% |
| | 4.97 | 34.27 | 16.6% | 0.0060 | |
| | 4.92 | 33.92 | | 0.0061 | |
| | 5.23 | 36.06 | | 0.0065 | |
| | 5.33 | 36.75 | | 0.0061 | |
| | 2.81 | 19.38 | | 0.0046 | |
| | 3.86 | 26.61 | | 0.0063 | |
| O | 2.73 | 18.82 | | - | |
| | 2.92 | 20.13 | | - | |
| | 2.46 | 16.96 | 2.72 ksi | - | |
| | 2.77 | 19.10 | 18.75 MPa | - | |
| | 2.70 | 18.62 | 5.5% | - | |
| | 2.63 | 18.13 | | - | |
| | 2.86 | 19.72 | | 0.0088 | |

## 6.2 Behavior Under Repeated Compressive Loads

A representative example of behavior under repeated loading is

depicted with the load-deflection relation seen in Fig. 6. For this particular specimen fabricated with Type O mortar, the sustained stress was equal to 50% of the ultimate static strength, and the single-amplitude alternating stress was equal to 40% of this value. Failure was observed at 40 cycles of loading.

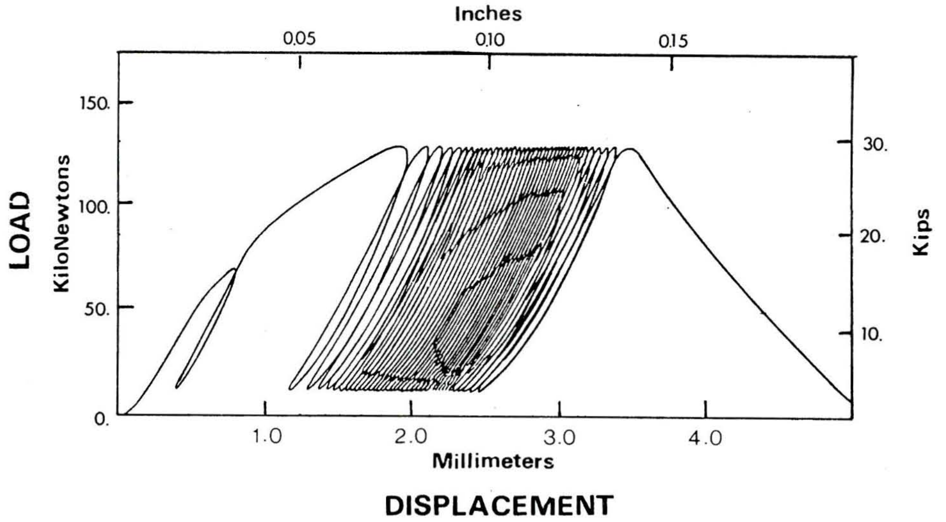


Fig. 6 Behavior of Test Prism Under Repeated Force (Type O Mortar)

Two characteristics of this curve are distinctly different from the curve obtained with monotonically increasing loadings (Fig. 5). One, axial deformation increased without an increase in maximum compressive stress. Residual deformations accumulated for each cycle. These deformations were largest for the initial cycle and diminished geometrically with each successive cycle until the sixth cycle before failure when a reversal in this tendency was observed. Two, failure of the specimen occurred at a maximum stress, i.e., the value of sustained stress plus the value of alternating stress, less than that observed under static loading.

Although failure occurred at a lower maximum stress under repeated loading, the observed pattern of damage was quite similar to that observed for prisms under static loading. A vertical splitting crack was observed in the brick unit (Fig. 7). The cycle number at which this failure was observed is

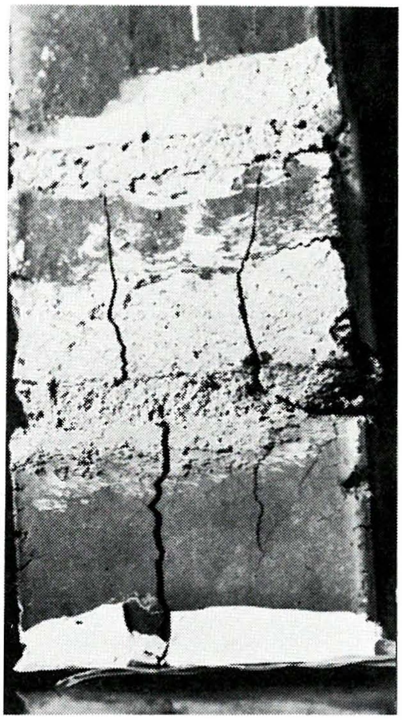

Fig. 7 Typical Damage

given in Table 3 for all specimens tested. Static strength after cycling is given in the table for specimens which did not fail before 180 cycles.

Specimens that did not fail before 180 cycles were essentially as strong as specimens subjected to static loading (Table 2). The reason for this may have been attributable to the fact that many of these specimens were lightly loaded, and effects of repeated forces were insignificant. Further loading of these specimens beyond 180 cycles probably would not have produced sizable strength reductions.

Table 3 Strengths of Test Prisms Under Repeated Forces

| Test Prisms with Type 0 Mortar | | | | Test Prisms with Type S Mortar | | | |
|---|---|---|---|---|---|---|---|
| Specimen Number (1) | Sustained/ Alternating Force (2) | Failure at Cycle (3) | Compressive Strength after Cycling (psi) (4) | Specimen Number (5) | Sustained/ Alternating Force (6) | Failure at Cycle (7) | Compressive Strength after Cycling (psi) (8) |
| 0-1 | 0.2/0.2* | na | 2700 | S-1 | 0.2/0.2 | na | 4450 |
| 0-2 | | na | 2690 | S-2 | | na | 4800 |
| 0-3 | | na | 2650 | S-3 | | | 3070 |
| 0-4 | 0.5/0.2 | na | 2990 | S-4 | 0.5/0.1 | na | 5440 |
| 0-5 | | na | 2760 | S-5 | | na | 4570 |
| 0-6 | | na | 2310 | S-6 | | na | 4380 |
| 0-7 | 0.4/0.3 | na | 2440 | S-7 | 0.4/0.2 | na | 3610 |
| 0-8 | | na | 3010 | S-8 | | na | 4560 |
| 0-9 | | na | 2630 | S-9 | | na | 3930 |
| 0-10 | 0.6/0.2 | na | 2920 | S-10 | 0.3/0.3 | na | 4560 |
| 0-11 | | na | 2300 | S-11 | | na | 3600 |
| 0-12 | | na | 2860 | S-12 | | na | 4420 |
| 0-13 | 0.5/0.3 | na | 2950 | S-13 | 0.6/0.1 | na | 4730 |
| 0-14 | | 1 | na | S-14 | | 1 | na |
| 0-15 | | 74 | na | S-15 | | 1 | na |
| 0-16 | | 36 | na | S-16 | | na | 4310 |
| 0-17 | 0.4/0.4 | 69 | na | S-17 | 0.5/0.2 | na | 4260 |
| 0-18 | | 96 | na | S-18 | | 135 | na |
| 0-19 | | 116 | na | S-19 | | 1 | na |
| 0-20 | 0.7/0.2 | 15 | na | S-20 | 0.4/0.3 | na | 4130 |
| 0-21 | | na | 3020 | S-21 | | 1 | na |
| 0-22 | | 12 | na | S-22 | | 7 | na |
| | | | | S-23 | | 50 | na |
| 0-23 | 0.5/0.4 | 4 | na | | | | |
| 0-24 | | 3 | na | S-24 | 0.7/0.1 | na | 5250 |
| 0-25 | | 1 | na | S-25 | | 1 | na |
| 0-26 | | 40 | na | S-26 | | 1 | na |

* Percentages of nominal static strength (Table 2)
Note: 1.0 psi = 0.00690 MPa

For those specimens that did fail during cyclic loading, a wide variation was observed in the cycle number at which failure occurred, particularly for specimens built with the stronger Type S mortar. For example, out of a total of four specimens subjected to the same loading history (60% sustained, 10% alternating) two specimens failed during the first cycle while two other specimens survived 180 cycles. This may have been because of the large deviation in strength values for specimens with this type of mortar (0.17 coefficient of variation).

It is clear from results of the Type O specimens that the

maximum value of compressive stress will not always be a reliable indicator of whether cyclic failure should occur or not. For example, where maximum stress was 80% of ultimate, all of the specimens of a group of three failed for 40% alternating stress, three out of four specimens failed for 30% alternating stress, and none of three failed for a 20% alternating stress. This behavior was not as clear for the Type S specimens, where 6 of 11 specimens failed below 180 cycles at a maximum total stress of 70% of ultimate. This difference may be attributed to the accumulation of residual tractions which occurs at a more rapid rate for the Type S specimens than for the Type O specimens. For a relatively low number of prescribed load cycles, such as 180, most of the Type S specimens may have been affected by cycling, whereas definitely not all of the Type O specimens were. For Type O mortar specimens, the amplitude of the alternating stress appeared to be significant.

The data listed in Table 3 are presented graphically in Figure 8 to show the interaction relationship of alternating and sustained force. A clear circle or square is used to show combinations of alternating and sustained force that resulted in failure of all or the majority of specimens in a particular group. A solid triangle designates a group of specimens that survived 180 cycles. The shaded upper half of the figure represents all cases where the alternating force would exceed the sustained force, i.e., net tension (which was not examined). The line at 45 degrees and intercepting unity on both abscissa and ordinate is the locus of combinations summing to 1.0, or the strength that is assumed for monotonically increasing forces.

The safe range has been defined in Figure 8 by extending a line through the data representing no failure and the abscissa at unity (to include the static load case). Specimens with the stronger Type S mortar were more vulnerable to alternating forces than specimens with the weaker Type O mortar. Maximum combined stress was 60% of ultimate static stresses for Type S specimens, and 70% to 80% for Type O specimens. This observation is reasonable based on the proposed theory because the stronger mortar would induce larger lateral tractions per cycle in the brick than would the weaker mortar. The number of cycles to failure would therefore be less for specimens with the stronger mortar.

The effect of the amplitude of alternating stress may be seen by examining the tendency to accumulate deformation with cycling. The total axial shortening of a test prism is plotted versus cycle number in Figure 9 for specimens fabricated with each mortar type. Curves are ranked from top to bottom in the figure according to the amount of alternating stress. The maximum stress is the same for each specimen type. A sudden increase in the slope of a curve indicates when failure was imminent. It is clear from this figure, that failure occurred earlier for specimens subjected to larger amounts of alternating force. Furthermore, the accumulation of deformation was much more rapid for specimens with the stronger Type S mortar.

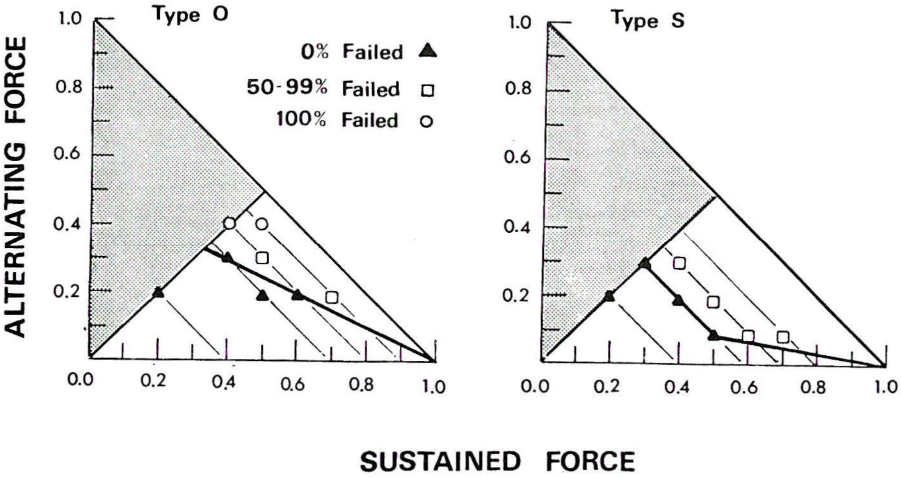


Fig. 8 Interaction of Alternating and Sustained Forces

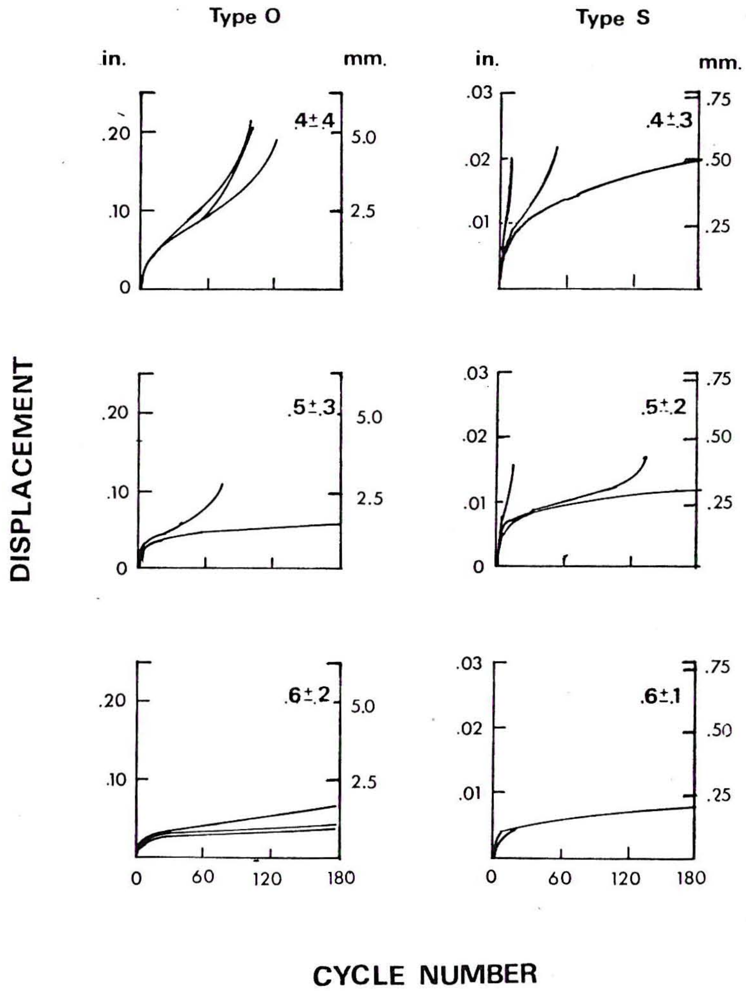


Fig. 9 Effect of Amplitude of Alternating
Stress on Accumulation of Deformation

## 7. CONCLUSIONS

A sizable reduction in compressive strength of clay-unit masonry may occur as a result of repeated forces. Tensile splitting of brick units was observed at stress levels as low as 70% of average ultimate static strengths. Strength reductions were observed to be influenced by mortar strength, the amplitude of the alternating stress and the number of cycles.

Specimens fabricated with relatively strong mortar (Type S) were found to be more sensitive to repeated forces than specimens with a weaker mortar (Type O). Residual deformations per cycle were larger for Type S specimens and failure occurred within fewer cycles. Strength reductions were larger for specimens with the stronger mortar.

The authors suggest that a mathematical model for masonry subjected to repeated compression could be formulated based on the coupling of elastic straining of a brick unit with the inelastic straining of confined mortar. Reductions in splitting strength of a brick unit as a result of cyclic forces could also be included in the model.

Suggestions for future research include this formulation based on experimental investigations of the behavior of constituent materials subjected to multiaxial repeated stresses. Moreover, effects of repeated compression on response of test prisms fabricated using different types of masonry units, mortars, grouting procedures, and reinforcing schemes should be studied.

## 8. ACKNOWLEDGEMENTS

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