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SEISMIC RESPONSE OF COMPOSITE MASONRY IN NEW AND EXISTING STRUCTURES

by

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This report summarizes the results of experimental and analytical research on the behavior of composite masonry walls, subjected to inplane loads on only one wythe. Most of the effort in this research has been focused on the determination of shear stresses in the collar joint, both analytically and experimentally, due to the vertically applied loads on the block wythe. Finite element models have also been developed to predict these shear stresses due to creep in composite masonry, and due to shrinkage and moisture expansion. Some success has been achieved to estimate the variation of shear stresses in the collar joint computationally. The experimental results have given the average values of shear stresses in the collar joint at which delamination of the two wythes in a composite wall takes place. Recommendations for future research are presented.

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ABSTRACT

This Final Report summarizes the results of the experimental and analytical research on the behavior of composite masonry walls, subjected to inplane loads on only one wythe, that has been conducted at Clemson University during the last three years. The details of the experimental and analytical phases have previously been reported in five Interim Reports that were submitted to the National Science Foundation and are cited in this document.

Most of the effort in this research has been focused on the determination of shear stresses in the collar joint, both analytically and experimentally, due to the vertically applied loads on the block wythe. Finite element models have also been developed to predict these shear stresses due to creep in composite masonry, and due to shrinkage and moisture expansion. Some success has been achieved to estimate the variation of shear stresses in the collar joint computationally. The experimental results have given the average values of shear stresses in the collar joint at which delamination of the two wythes in a composite wall takes place.

It is recommended that the present research efforts be continued to investigate the behavior of composite walls when they are subjacted to various combinations of vertical and horizontal loads. This loading configuration is quite realistic and is often encountered in real life cases. Variations of some other parameters are also suggested.

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INTRODUCTION

The recent development of engineered masonry design standards for brick masonry (1)* and concrete masonry (2) has resulted in widespread design and construction of masonry loadbearing structures. Using the new standards, buildings of either brick or concrete block are designed using rational engineering principles. Prior to the introduction of the new standards, masonry was empirically designed using rule-of-thumb methods (3). The performance of masonry structures designed under the new standards is expected to be considerably superior to those designed previously.

Composite masonry walls usually consist of a single wythe of brick and a single wythe of concrete block with a parged or grouted collar joint forming a bond between the two wythes. It is estimated that about 15% of all nonresidential masonry construction is composite, most of which has been or is being designed without any consideration of the earthquake loads but is located in the earthquake prone regions of the Central and Eastern United States. Most standards (1, 2, 3, 4), though they have provisions for design of composite walls, are not based on experimental data. Standards presently being developed by The Masonry Society and the American Society of Civil Engineers require theoretical and experimental input to justify the inclusion of composite design. Before standards for composite construction can be developed, fundamental research is required to evaluate and predict the static and cyclic performance of composite masonry walls.

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* Numbers in parenthesis refer to literature cited in the reference section.

Only a minimal amount of experimental research has been performed on composite masonry. It has been limited in scope and is not sufficient to justify the writing of a design standard. In particular, little information is currently available concerning the flexural and shear strength of composite masonry subjected to static and cyclic loads.

In order to obtain the necessary information to predict the strength of composite masonry, analytical and experimental research has been conducted at Clemson University during the last four years. Although some information on the behavior of composite masonry has been obtained, much work still needs to be done before the true strength and behavior of composite masonry can be established. This report summarizes the results of the present research and attempts to present some of the major questions that still need to be answered concerning the strength of composite masonry. Before describing the exact nature of the needed future research, the states of the previous and current research are presented.

Previous Research

Only three previous research programs have dealt with composite masonry. One was a cooperative project between the Brick Institute of America and National Concrete Masonry Association, the second was a project at the National Bureau of Standards, and the third project was conducted at the University of Texas at Austin. The BIA/NCMA program resulted in completion of two phases (5, 6) which included testing of prisms and walls in compression only.

Fattal and Cattaneo at the National Bureau of Standards (7) tested thirty prisms and sixteen walls of composite masonry. They found reasonable agreement between theoretical and measured results using the concept of transformed section. Inspection of specimens loaded to failure revealed no apparent distress in the collar joint, though all specimens were reinforced with truss-type joint reinforcing. They developed an interaction diagram which predicted failure at combined axial load and bending moment. A moment magnifier technique was applied to the test data, and the agreement was good.

The structural effects of differential movements in composite masonry walls have been recognized by Grimm and Fowler in their research conducted at the University of Texas at Austin (8). Moisture expansion in brick masonry combined with shrinkage in concrete masonry, as well as different coefficients of thermal expansion, can result in the development of shear stresses in a collar joint that have substantial magnitude. These stresses occur before any applied loads are considered.

Related research that can be applied to an understanding of composite masonry has been performed on masonry consisting exclusively of brick or concrete block (9-20). Hegemier _et_ _al_. (21, 22, 23) have developed constitutive relationships and failure criteria for concrete masonry subjected to biaxial stress. Other failure criteria for brick and block masonry have been developed by Hamid and Drysdale (24). Mayes _et_ _al_. (25, 26, 27) have completed a series of approximately 80 in-plane shear tests on single pier test specimens including concrete block, hollow clay brick and grouted-core clay brick. They evaluated the effect of horizontal reinforcement and partial grouting on ductility. This research did not include composite masonry, and cannot be directly applied to it.

Ayra and Hegemier (28) have developed a finite element micro-model to predict the non-linear response of concrete masonry assemblages, which includes the pre- and post-fracture behavior of joints and accounts for masonry cracking. They applied the results of their model to test results performed at the University of California, Berkeley, and obtained good correlation.

Gülkan et al. (29) subjected single-story concrete masonry structures to simulated earthquakes. Thus far, the scope has been limited to reinforced concrete masonry, but tests on clay masonry structures are under way at present.

Current Practice

The BIA Standard (1) permits the design of composite walls if the stresses do not exceed the allowable for the weaker unit. The full wall thickness is permitted, and requirements are given for bonding with metal ties. No consideration is given for differential movement or interlaminar shear stresses between the dissimilar wythes at the collar joint. The NCMA Standard (2), ANSI A41.1 (3), UBC (30) and Southern Standard Building Code (31) have composite masonry provisions which are essentially identical to those of BIA (1). BOCA (32) permits the use of composite masonry but does not guide its design.

The American Concrete Institute has recently written a code for concrete masonry (4). It recommends the use of the transformed section concept for flexural and axial design of composite walls, a departure from the other codes. There is no mention in this code of limiting shear stresses at the collar joint caused by differential movement or external loads. Other codes are being developed by the Masonry Society and the American Society of Civil Engineers. Neither will have documentation or justification for any recommendation they make for the design of composite masonry walls.

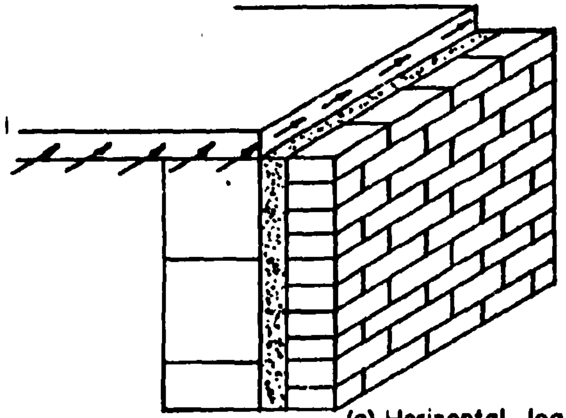
Research Needs

In order to properly design new, as well as evaluate existing composite masonry walls for both static and seismic loading, the question of inplane shear stresses in the collar joint must be resolved. Sources of these stresses are differential movement of dissimilar wythes of masonry, inplane loads applied to only one wythe, and flexural shearing stresses produced by out-of-plane loads.

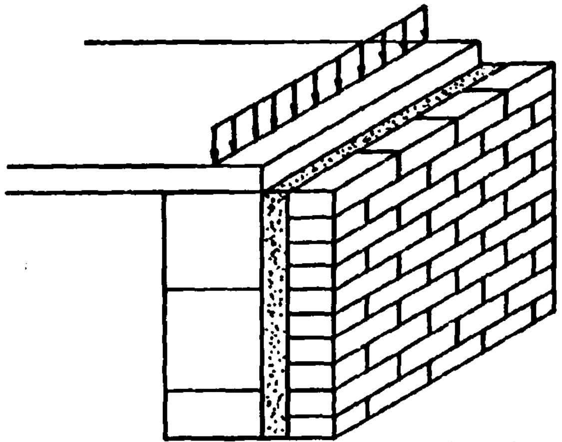
As shown by Grimm and Fowler (8), shear stresses in a collar joint due to differential movement of dissimilar wythes can be of substantial magnitude and must be included in the development of any analytical model.

In many details of floor-wall connections, the floor rests on the interior wythe of a composite wall (Fig. 1). The vertical gravity loads and horizontal shear loads are transferred directly from the floor system to the inner wythe. Some of these loads are transferred to the exterior wythe through shear stresses in the collar joint (Fig. 2). The details of this load transfer mechanism and the magnitude of the resulting shear stresses are at present not well known and understood. However, if delamination in the collar joint occurs due to a combination of the load-induced stresses and the differential movement stresses, the inner wythe will carry virtually all the load. Results of delamination could be catastrophic.

It can be shown that flexural shear stresses resulting from out-of-plane loading for typical wind loads and wall spans are of the order of 5 psi or less, when calculated by a simple strength of materials approach (33). A stress of such magnitude can be regarded as negligible. Stresses from other out-of-plane loadings, such as earthquakes, may be



(a) Horizontal loading



(b) Vertical loading

Fig. 1 Application of Loads to a Composite Masonry Wall

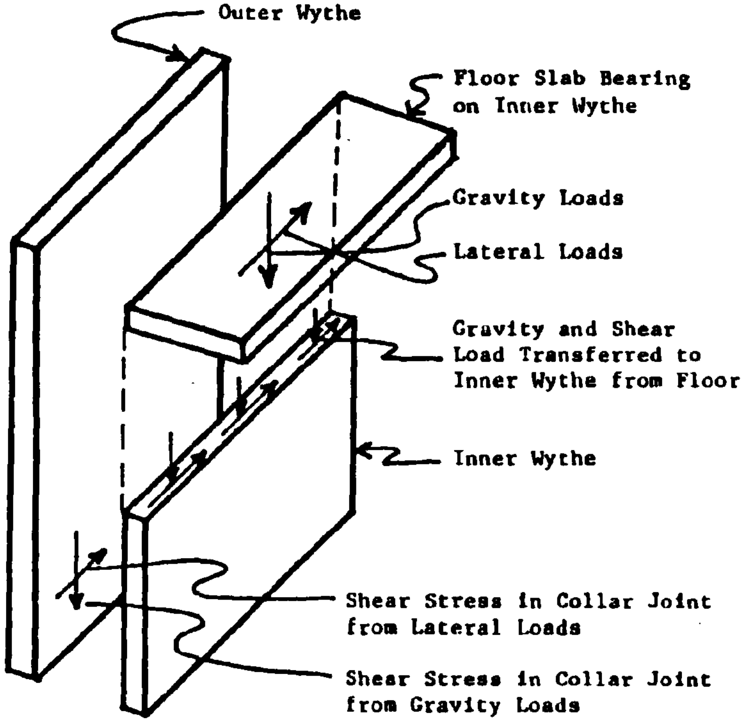


Fig. 2 Load Transfer from Slab Bearing on Inner Wythe of a Composite Wall

larger and significant, but will be considered in subsequent studies after a better understanding of the in-plane behavior of composite masonry has been achieved.

Of the three sources of inter-laminar shearing stresses mentioned earlier, those resulting from floors bearing on inner wythes, and due to differential movement in dissimilar wythes because of shrinkage and thermal expansion as well as creep, are felt to be most critical. These may be additive to each other and should, therefore, be considered.

CURRENT RESEARCH

Research at Clemson University

The writers have been engaged in research, which is a combined analytical and experimental effort, during the last three years to improve the understanding of the behavior of composite masonry walls. This research has been supported by the National Science Foundation. The results of this research are reported in the five interim reports that have been submitted to the National Science Foundation (33-37). In addition, various aspects of the findings have been published in the proceedings of national and international conferences (38-48). The specific objectives and results of this research at Clemson University may be summarized as follows:

Analytical Phase

The primary objective in this phase was to develop a two-dimensional finite element model that was capable of predicting the shear stress distribution in the collar joint and normal stress distribution in the wythes of composite masonry walls subjected to vertical in-plane loads. It was considered desirable that the analytical model should also have the capability to compute the corresponding stresses in the wythes and the collar joint due to creep, moisture and thermal strains. In addition, the model should be able to incorporate the presence of the bed reinforcement across the collar joint and determine whether any separation or cracking would occur between the wythes and the collar joint due to the presence of excessive interlaminar shear. As the application of a completely three dimensional finite element model would be cost prohibitive and unnecessary, it was proposed to develop only a quasi two-dimensional model.

The Finite Element Model. A two-dimensional finite element model that had previously been developed for analyzing composite masonry walls for linear elastic materials, and was capable of computing only shear stresses in the collar joint (39), became the basic program utilized for further development. As a first step in this development, capabilities were built in the program to compute normal as well as all shear stresses in the collar joint (40). Capability to determine collar joint shearing stresses along the longitudinal direction of the wall (this capability did not exist in the previously available program) is necessary as these stresses can be large in composite walls with openings or in walls that are not completely loaded along the whole length of the wall. This newly developed program was utilized to compute stresses in a composite masonry wall with a window opening. The resulting stresses were as anticipated and exhibited large variations along the length of the wall (40).

Crack Modelling at the Collar Joint-Wythe Interface. It has been shown in various numerical solutions (34, 39, 40) that the shear stress distribution in the collar joint due to vertically applied loads on only one wythe is non-uniform with the maximum value near the point of load application (Fig. 3). The vertical load transfer from the loaded wythe to the unloaded wythe occurs essentially in the very top of the wall. This non-uniform shear stress distribution with a high value near the point of load application could be instrumental in initiating a crack in the collar joint that could lead to separation of the collar joint from the wythes and eventual complete failure of the composite wall. To predict this phenomenon analytically, a failure criterion based on a limiting shear stress in the collar joint has been developed and

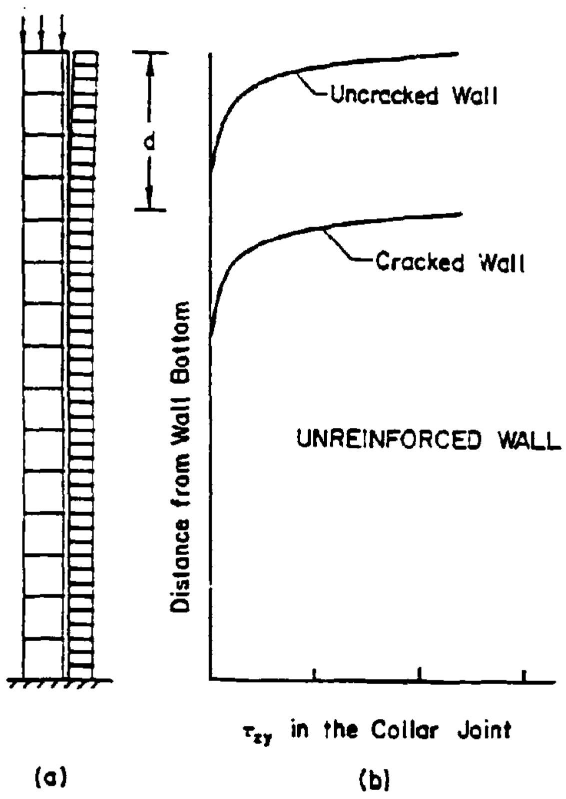


Fig. 3 Collar Joint Shear Stress Distribution in a Cracked and Uncracked Unreinforced Wall

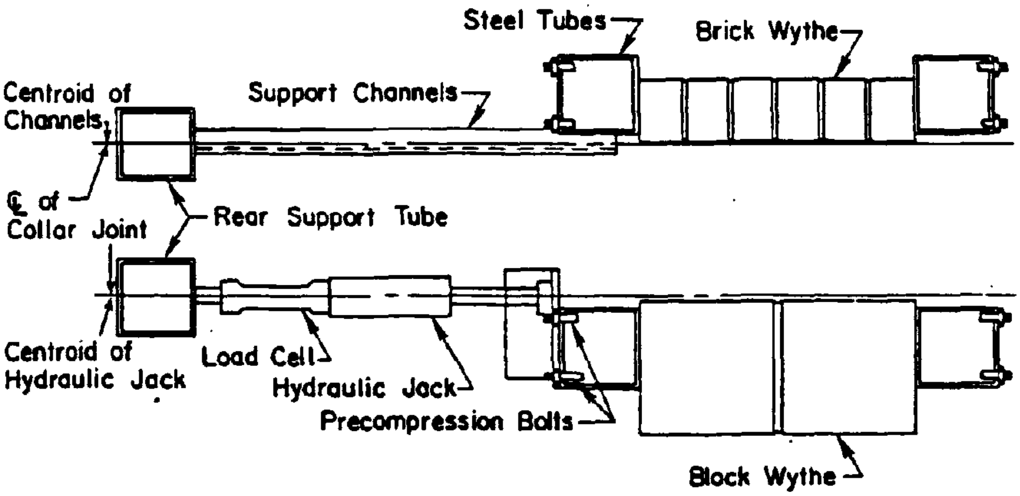


Fig. 4 Schematic Drawing of a Specimen in the Test Apparatus

proposed by the Principal Investigator and his colleagues (34, 44, 45). This failure criterion has been built in the two-dimensional finite element program for the analysis of unreinforced composite masonry walls.

For the composite masonry walls that have truss or ladder type of reinforcement in the bed joints across the collar joint, it is assumed that the principal of shear friction is applicable. Once cracks develop at the wythe-collar joint interface, and relative displacements between the two surfaces occur, the surfaces also separate perpendicular to each other due to their coarseness. This separation produces tension in the reinforcement spanning across the crack which in turn produces compressive forces between the surfaces. These compressive forces help in resisting further relative movement between a wythe and the collar joint due to friction and are instrumental in arresting the crack. This shear-friction concept was also incorporated in the two-dimensional finite element program, details of which may be found in References (34, 44, 45).

A 10 ft high composite masonry wall subjected to 7 k/ft vertical loadon the block wythe was analyzed using the newly developed 2-dimensional finite element program. As expected, it was found that the unreinforced wall started to develop cracks near the top edge and these cracks propagated all the way down the wall until the two wythes were completely separated. On the other hand, shear friction forces were mobilized in the reinforced composite wall which arrested the growth of cracks at approximately 14 inches from the top of the wall for the given applied load. It is,nevertheless, possible that, if the magnitude of the applied load is too large for the small shear friction forces which develop due to small amount of reinforcement, the cracking at the interface of a wythe and the collar joint would not stop and the composite wall would fail due to separation of the two wythes.

Finite Element Analysis of the Test Apparatus. A schematic drawing of the test apparatus utilized in testing 16" by 16" composite wall specimens is shown in Fig. (4). This apparatus was designed specifically with the objective that the collar joint was subjected only to pure shear forces. However, the placement of the specimen in the apparatus required that the specimen be held in place by tightening some precompression bolts. Figure 5 shows a specimen in place wihtin the test apparatus.

Although all precompression bolts were tightened equally so as not to introduce any initial shear stresses in the collar joint, finite element analyses indicate that this was not the case. Consequently, some initial shear stresses might have been introduced in the collar joint. As the precompression in the bolts was not measured exactly, these initial stresses could have been variable, thus giving different failure loads for the specimens. Details of these analysis are given in Reference (34). Based on these analyses, it was recommended that some other testing apparatus that did not require precompression be used.

Collar Joint Shear Stresses Due to Creep Strains. As brick and block masonry experience creep strains when subjected to loads (49-53), their influence on the integrity of a composite masonry wall should be investigated. It has been reported in the literature that creep in masonry can be defined in terms of specific creep, i.e., creep per unit of stress, with respect to time (49, 50). Thus, a creep curve for a material becomes a uniquely defined curve from which creep at various stresses can be found for any interval of time. Specific creep curves

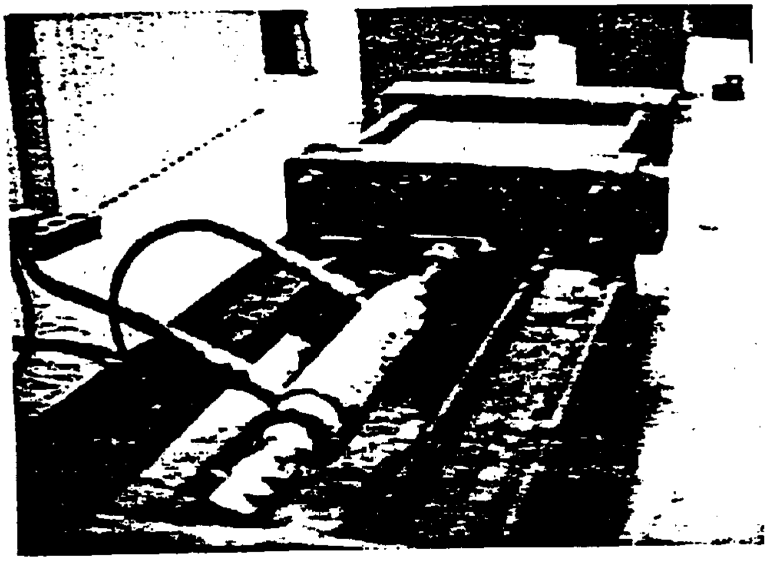


Fig. 5 Steel Frame and Jack in the Test Apparatus

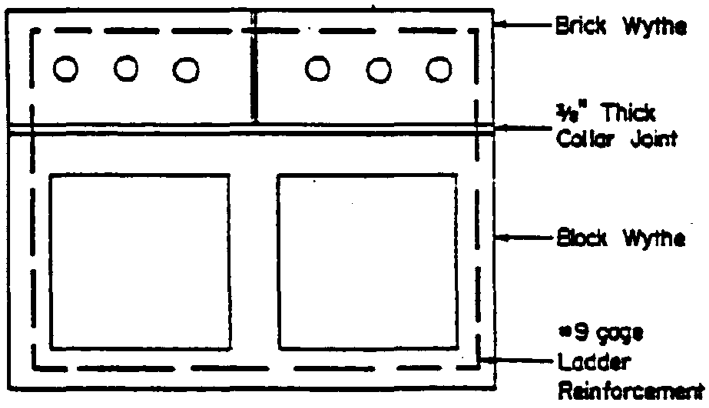


Fig. 6 Composite Masonry Wall Cross-Section with 3/8 in. Collar Joint

for brick and block wythes were developed from the creep data available in the literature and were stored in the computer memory. The nonlinear behavior of the specific creep vs. time curve was treated as a piecewise linear phenomenon.

The two dimensional finite element program for the composite masonry walls was modified and developed further to include creep strains as initial strains. Examples of composite masonry walls subjected to vertical loads on the block wythe were analyzed elastically for stresses and strains due to loads. Analyses were also carried out to find changes in the stresses and strains due to creep in the brick and block wythes for approximately 300 days (35, 37, 52, 43, 46). It was found that although the normal strains in both wythes almost double due to creep, the corresponding normal stresses vary by only 20%. On the other hand, the shearing strains and stresses in the collar joint essentially remain the same. Consequently, it can be deduced that the creep in a brick or block wythe in composite masonry walls does not play a very significant role as far as the shear strength of the walls is concerned.

Effect of Moisture Strains. It is also well known that bricks expand due to ambient moisture and blocks shrink with time when left to the atmosphere (8, 49, 52). Because the composite masonry walls under investigation are constructed with one wythe of brick and one wythe of concrete block, and are connected together by mortar or grout in the collar joint, it was found necessary to calculate shear stresses in the collar joint due to moisture strains alone.

Two types of analyses were carried out using the finite element program. In the first, the analyses were time independent and the moisture strains (expansion in brick and contraction in block) were calculated from the corresponding coefficients of expansion and shrinkage given by Grimm and Fowler (8), which are the maximum values over a long period of time. From these time independent analyses, it was discovered that the normal strains in the wythes had approximately the same magnitude as those due to the maximum allowable normal load. The maximum shear strain in the collar joint, on the other hand, was three times larger than that due to the maximum allowable load (35).

Analyses were also conducted that were time dependent and utilized moisture strain vs time curves available in the literature for brick and block masonry (49, 52). These analyses are quite similar to those for creep and were performed for up to 225 days when most of the moisture strains have ceased to occur. These analyses indicated that the normal strains in the wythes were approximately two and a half times larger and the maximum shear strains in the collar joint three times larger than the corresponding strains due to the maximum allowable applied load.

It should be pointed out that the maximum allowable applied load was based on the recommended practice (54) and was less than 20% of the compressive strength of concrete block masonry. Thus, the maximum stresses due to moisture, even though three times larger than those due to the applied loads, are equal to only about one half of the magnitude that would be caused by the application of the failure loads.

Experimental Results

The experimental phase of the research at Clemson is described in detail in References (33, 36, 48). It was essentially subdivided into two parts. In the first, 16 in. x 16 in. composite masonry wall specimens were made from two concrete blocks and six layers of bricks connected to each other by a 3/8 in. slushed collar joint (Fig. 6). In the second part, the specimens were of the same dimensions except that a 2 in. grouted collar joint was used to connect the brick and block wythes.

Specimens With 3/8 in. Slushed Collar Joint. A total of 60 specimens were manufactured in which the variables for the materials consisted of the low and high absorption bricks and blocks, Type N and Type S mortar, and specimens with and without the ladder type reinforcement. Six specimens of each type were produced, three of which were tested statically and the remaining three cyclically.

The testing apparatus shown previously in Fig. 4 was designed such that the specimens could be subjected to pure shear. A photograph of this apparatus with the specimen in place has also been shown earlier in Fig. 5. The testing apparatus performed satisfactorily except for some precompression effects that will be discussed later. The results of the tests performed on 3/8 in. slushed specimens may be summarized as follows:

1. The presence of the small amount of ladder type bed reinforcement that is generally provided in composite masonry walls does not increase the shear strength of the collar joint to any significant degree.

2. The shear strength of composite masonry increases sharply with increased mortar compressive strength form Type N to Type S mortar.

3. Generally speaking the absorption type of brick or block used in a composite masonry specimen has little effect on the shear strength.

4. The shear capacity of specimens subjected to cyclic loads is, in general, much smaller than the corresponding capacity if subjected to static loads.

5. The average shear stress in the collar joint at failure of all specimens made with Type S mortar and subjected to static loads was approximately 56 psi.

6. The average coefficient of variation of all types of specimens was approximately 39%.

Specimens With 2 in. Grouted Collar Joint. The procedure and program of testing for the specimens with 2 in. grouted collar joint was very similar to that for specimens with 3/8 in. slushed collar joint. The same testing apparatus was utilized except that some modifications were made to insure that no bending moments were acting on the specimen during load applications (36).

A total of 84 specimens were tested in this experimental phase, about one half of these statically and the rest cyclically. The primary variables (as for the specimens with 3/8 in. collar joint) were, the absorption type of bricks and blocks, Type S and Type N mortar, and the presence or absence of the ladder type reinforcement in the collar joint. The results of these tests may be summarized as follows:

1. The shear strength of the collar joints was the same whether Type S or Type N mortar was used in the wythes.

2. Most of the collar joint failures and separations occurred at the brick-grout interface. In addition, composite walls built with high absorption brick resisted larger loads compared to those built with low absorption brick. The block absorption rate, on the other hand, had

no significant influence on the shear strength of the collar joint.

3. Specimens that were loaded statically exhibited a much larger shear strength than those loaded cyclically. Average shear strength of all specimens loaded statically was 66 psi whereas the corresponding strength of cyclically loaded specimens was 36 psi.

4. The presence of the ladder type reinforcement in the bed joint had no significant influence on the shear strength of the specimens.

5. The average coefficient of variation for all specimens tested was 24%.

Current Research by Other Investigators

As far as is known, the only other research currently being conducted on composite masonry is as follows:

Tests at Iowa State University

At Iowa State University, Professor Porter and his colleagues are engaged in a research program which involves testing of 4 ft. x 6 ft. composite masonry panels that are built with 2 in. grouted collar joint (55). Their specimens are subjected to both the vertical and horizontal inplane loads at the top which is free to move (the bottom of the panels is fixed). These loads are uniformly distributed and are applied to both wythes. The loading frame used by Porter et al. is shown in Fig. 7.

The panels are subjected to a constant maximum allowable vertical load specified by the ACI Code (4) and a stepwise increasing horizontal load until failure. Both block-brick and brick-brick composite walls are tested to failure and the results are given in terms of the average stress resisted by the cross-sectional area upon which the loads are applied. The various modes of failure (i.e., separation of either wythe from the collar joint or crushing of the wythes near the corners) are

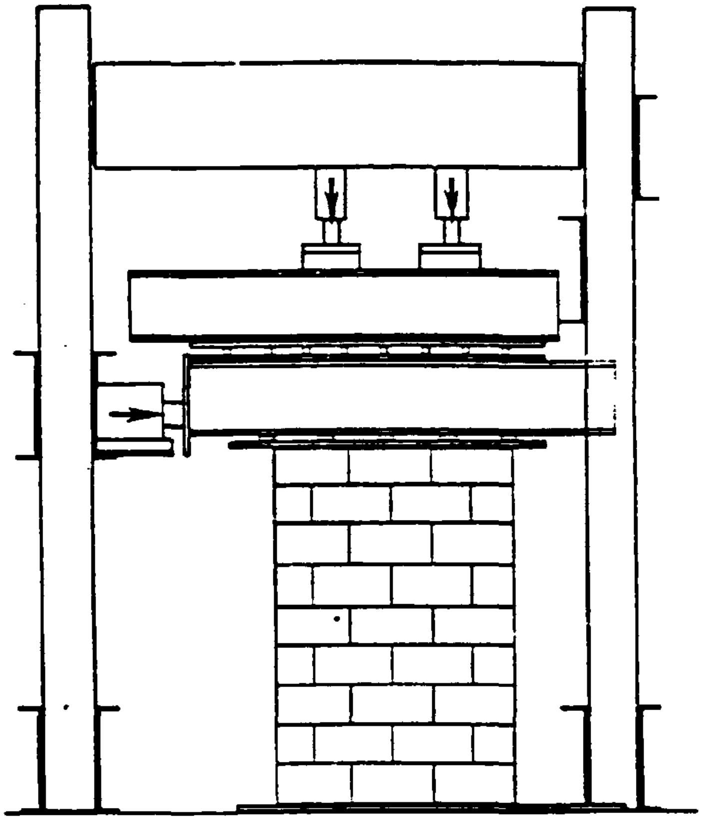


Fig. 7 Loading Mechanism Utilized at the Iowa State University

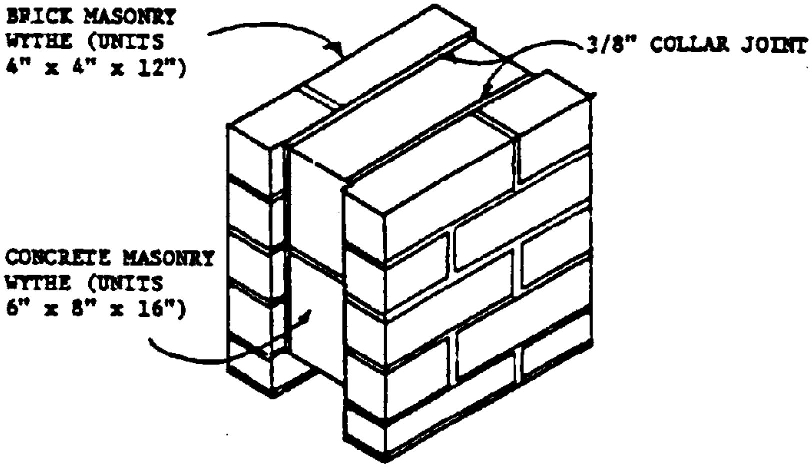


Fig. 8 Test Specimen Used at the Pennsylvania State University

observed and recorded. No attempts have been made in this study to determine the actual amount or distribution of shear in the collar joint. Consequently, shear strength of the collar joint due to loads acting only on one wythe cannot be established from their tests.

Research at The Pennsylvania State University

Professor Louis F. Geschwindner of the Department of Architectural Engineering at The Pennsylvania State University has conducted limited number of tests on 16 in. x 16 in. composite wall specimens (56). His specimens are specially designed for laboratory testing purposes and have two wythes of brick connected to single wythe of concrete block with two 3/8 in. collar joints as shown in Fig. 8. The collar joints are filled with either mortar (Type S and Type N) or fine aggregate grout. In addition, the horizontal bed joint in the concrete block masonry is either reinforced with #9 wire (or 3/16 in.) truss type reinforcement or left unreinforced. Twenty one specimens (three of each kind) have been tested by applying distributed vertical load on the middle block wythe, which produces essentially shear in the collar joint in addition to a small amount of bending. Results of these tests may be summarized as follows:

1. There is no appreciable increase in the shear strength of the collar joints due to the presence of the reinforcement.

2. The failure in each case is abrupt and does not show much ductility.

3. For most of the specimens, the shear failure occurs at the brick-collar joint interface.

4. The grouted joints show better workmanship between the wythes and collar joint and consequently are stronger in resisting shear.

After analyzing the test results, Prof. Geschwindner and colleagues have claimed that the shear strength of the collar joint is directly proportional to the compressive strength of the collar joint material. Accordingly, they have proposed various formulas to predict the shear bond strength of collar joints. However, it appears to the authors of this report that the shear strength predicted by the proposed formulas is not assured due to a wide scatter in the results. It is disturbing to note that the shear strength of some of the specimens built with stronger Type S mortar is lower than of those built with weaker Type N mortar. The shear strengths of specimens with grouted collar joint appear in general to be higher than those built with mortar in the collar joint. This higher strength could be attributed to a better bond and workmanship between the grout and the wythes. However, additional tests, particularly with larger specimens, need to be conducted before any design formulas for the shear bond strengths of the collar joints in composite masonry walls can be established.

Research at the University of Florida

At the University of Florida, Professor Morris W. Self and his associates have been engaged in research on composite masonry since 1981 that has been supported by the Masonry Research Foundation. The first phase of this research has focused its attention on the determination of the nominal compressive strength of composite masonry prisms. In particular, the effect of some important variables on the compressive strength is investigated. Some of these variables are: (1) shape and size of the prisms, (2) strengths of the masonry units, mortar and grout, (3) thickness of the collar joint, and (4) loading configuration on the prisms, especially the effects of eccentricity on the prism strengths. The results of these prism tests have been summarized by Professors Self and Lybas and submitted to the Masonry Research Foundation for review (57). Although very useful for a better understanding of the strength of composite masonry prisms, this research does not yield any information on the shear strength of composite masonry walls subjected to inplane loads on one wythe.

Evaluation of the Current Research

The results of the current research on composite masonry subjected to inplane loads reported in the previous sections are evaluated and summarized as follows:

Finite element computer programs have been developed from which it is possible to predict the distribution of shear stresses in the collar joints of composite masonry walls subjected to inplane loads acting only on one wythe. Through the use of these quasi-two-dimensional programs, it is possible to ascertain the variation of shear stresses along the length as well as the height of a wall.

The finite element programs also have the capability to incorporate a simple shear failure criterion at the collar joint in addition to the development of the shear friction concept. It has been shown that the presence of the ladder type of bed reinforcement across the collar joint can activate shear friction forces and arrest the growth of cracks and eventual failure of the collar joint.

The ability to estimate time dependent creep strains in composite masonry walls due to loads has also been incorporated in the computer programs, in which it is assumed that the creep behavior for any material can be defined by the specific creep strain vs. time curve. From the creep analyses that were conducted, it can be concluded that although normal strains in the wythes more than double due to creep, the shear strains and stresses in the collar joint essentially remain the same. The computer programs also have the capability to compute strains and stresses in a composite wall due to expansion and shrinkage caused by moisture. From the moisture analyses conducted on the composite walls, it is shown that the normal stresses and strains in the wythes as well as the shear strains in the collar joint are approximately one half in magnitude compared to those due to failure loads. These results are based upon specific moisture strain vs. time curves that are available in the literature (49, 52). More data on moisture strains in masonry is urgently needed.

It is obvious from the results of the experimental research that the interface between the wythes and the collar joint is the natural weak region in composite masonry. It is also clear that the small amount of bed reinforcement normally provided in composite masonry across the collar joint is not sufficient to provide any additional strength. Although various absorption types of bricks and blocks are currently used in composite masonry, their influence on the shear strength of a collar joint appears to be minimal. It is clear, however, that the shear capacity of a collar joint diminishes greatly when it is subjected to cyclical loading.

The tests also tend to indicate that the shear strength of a collar joint generally increases with an increase in the compressive strength of the mortar used in the collar joint. This conclusion, however, is not definitive as the coefficient of variation of the obtained results is too large. Additional tests, particularly on large specimens of the size 4 ft. x 6 ft. are necessary before any specific recommendations about the strength of the collar joint based on the mortar strength can be made.

It should be noted that the experiments conducted so far have only given the average failure shear stress in the collar joint. The size of the specimens utilized has been rather too small to determine the distribution of shear stress in the collar joint experimentally. It would be highly desirable to estimate the strain variation in the collar joint experimentally using larger size specimens.

In the tests conducted on composite masonry by the Principal Investigator and his colleagues using the pure shear device developed at Clemson (33, 36), it was reported that some specimens failed in shear during their placement and precompression. Although, the testing device ideally should not have caused any shear stress in the collar joint during precompression, unequal tightening of the precompression bolts possibly did create some shear. This was also shown to be true by the finite element analyses (34). Therefore, it is recommended that further tests should not be performed using this tesing device.

RECOMMENDATIONS FOR FUTURE RESEARCH

Research Objectives

The overall objective of this research is to provide further information to permit the assessment of the performance of new and existing composite masonry buildings when they are subjected to vertical and horizontal inplane loads due to gravity, earthquake and wind, and to develop criteria for their safe design and evaluation.

Before the performance of a complete composite masonry building can be determined, however, behavior of various components subjected to static and dynamic loads must first be established. The component performance can be obtained either experimentally or with an analytical model. It is obvious that the experimental approach would be extremely costly as tests for each component with many variables, such as brick-and-block strength, mortar strength, size of the collar joint, amount and shape of the steel reinforcement etc., would have to be carried out. On the other hand, if analytical models that yield load-deformation behavior of composite masonry in the linear and nonlinear pre- and post-fracture ranges could be developed and verified against results of a limited testing program, the whole procedure would be more economical as well as safe and acceptable.

From the research on composite masonry that has been conducted so far and described in the previous sections, it can be seen that the efforts so far have been to load the specimens perpendicular to the bed joints. This loading condition, though very important, is by no means the only one worthy of investigation. In many realistic situations, the composite walls would be subjected to horizontal in-plane loads due to wind and/or earthquakes, as shown in Fig. 1 (a) and Fig. 2, and could fail due to these loads.

The horizontal loads could be considered to act on the loaded block wythe of a composite wall from the diaphragm action of the slab, and could cause substantial amount of shear in the collar joint. The failure of the composite masonry wall thus may occur not only by delamination of the collar joint due to a combined action of the vertical and horizontal shears but also due to possible failure of the horizontal bed joints in the concrete masonry. The possibility of this failure mode is likely to exist in composite walls which are built with hollow concrete blocks and/or which have a minimal amount of vertical reinforcement. Consequently, it is quite important that experimental and analytical investigations be conducted to determine the strength of composite masonry walls subjected to a combination of vertical and horizontal in-plane loads.

Analytical Phase

The analytical phase of the recommended future research is largely based upon the experiences derived by the Principal Investigator from the research conducted by him during the last two years. In addition, failure criteria for brick and block masonry developed by other researchers should be utilized as appropriate (20, 22, 24, 28).

Although the vertical and horizontal loads acting in the plane of the block wythe cause only inplane displacements, the resulting shear stresses in the collar joint are in a direction perpendicular to the plane of the wall. Thus, the composite wall behavior is quasi-two-dimensional and a two-dimensional finite element model can be used to investigate the stress distribution in the wall. This two-dimensional finite element model with various capabilities has already been developed by the Principal Investigator as described under CURRENT RESEARCH. The model is capable of determining stresses and strains in the wythes as well as in the collar joint. Capabilities have been developed in this model to compute stresses in the wall due to moisture and creep strains based on elastic analysis. A simple failure criterion has also been built into the model that predicts cracking and eventual delamination of the collar joint and subsequent arrest of cracks due to shear friction affects of the reinforcement.

This finite element model should be developed further so that it is also capable of predicting failure of the bed joints in the wythes in addition to delamination of the collar joint. Various failure criteria for masonry, that have been proposed by the other investigators (20, 24, 28), should be studied and the most appropriate one incorporated into the existing computer program. In addition to the currently built-in simple failure criterion of the collar joint based on only the shear stresses, a more rigorous failure criterion based on the normal as well as shear stresses should be developed for the collar joint and incorporated in the computer program.

It has also been observed in the analyses of composite masonry walls (35, 37) that the block and brick wythes undergo loading as well as unloading during the creep period (of say a year or so). The unloading criterion for creep has not been built into the previously developed computer program. It should be incorporated in this program for a better assessment of the creep strains in composite walls.

Experimental Phase

Since the testing of large structural specimens is both expensive and time consuming, an experimental program should be developed in which only those material parameters are varied that have been found in the previous investigations to have a significant effect on the performance of a composite wall. In order to ascertain the effect of the specimen size on the shear strength of a collar joint, as well as to experimentally determine the shear stress distribution in the collar joint, use of larger specimens of the size 4 ft. x 6 ft. is recommended. The experimental phase should initially be restricted to static loading with the more complex dynamic loading to follow in the future.

Testing should take place on a loading rig similar to that designed by Porter *et al.* (55) and shown earlier in Fig. 7. The loads should be applied at the top of the block wythe of 4 ft. wide by 6 ft. high composite walls. The test program should be as follows: All specimens must contain standard #9 ladder type bed reinforcement. Half of the specimens should have a 3/8 in Type S mortar joint between the wythes and the other half a 2 in grouted collar joint. At each of the load configurations described in Table 1, three specimens should be loaded incrementally to failure. Consequently, the complete Experimental Phase will require testing of a total of 30 4 ft. x 6 ft. composite wall specimens. In addition, standard tests should be performed on the brick, block, mortar and grout used in the specimens.

TABLE 1. Load Configurations for Specimens in the Experimental Phase

Vertical Load	Horizontal Load
Zero	Increased until failure occurs.
50% maximum allowable load in the block	Increased until failure occurs.
100% maximum allowable load in the block.	Increased until failure occurs.
50% compressive strength of the block	Increased until failure occurs.
Increased until failure occurs	Zero

During the course of the wall tests, shear strain distribution in the collar joint should be determined. This can be done by using LVDTs to measure the differential movement of the protruding ends of metal bars embedded in the bed joints. Extreme care should be exercised to place the metal bars, which are parallel to the length of the wall, as close to the collar joint as possible.

Comparison of Analytical & Experimental Results

The theoretical and analytical development described above and its implementation into various computer programs could be achieved through computer runs of simple test problems. However, in order to verify the validity of the failure criteria, material properties, and the computer solution, the computer programs should be used in the failure analysis of the 4 ft. x 6 ft. composite wall panels which had been subjected to various combinations of vertical and horizontal in-plane loads as described in the experimental phase. The results of the two phases should be compared for various load levels and loading conditions.

Anticipated Results From The Recommended Future Research

The proposed research will yield various combinations of vertical and horizontal in-plane failure loads that can be applied statically to the loaded block wythe in composite masonry wall panels. From the shear strains that will be measured in the collar joint, it would be possible to estimate the path of the horizontal and vertical load transfer from the block to the brick wythe. The five vertical to horizontal loading combinations, that produce failure in composite masonry panels, will yield five points in a graph (vertical load per unit length vs. horizontal load per unit lenght) which would be used to draw a failure interaction envelope. One envelope each would be possible for composite wall panels with 3/8 in. slushed and 2 in. grouted collar joints. Safe design loads that can be applied to the block wythe in the plane of the wall could, thus, be derived from these envelopes.

In addition, computer programs would become available which could be used by engineers and designers to predict stress distributions in specific composite walls due to in-plane loads, as well as due to creep, moisture and thermal strains. Through the utilization of these computer programs, it would be possible to superpose stresses due to various effects and predict the safety of composite masonry walls. Development of cracking and failure in the wythes and/or the collar joint could be predicted. The programs could also be utilized to hypothesize the arrest of cracks in the collar joint by increasing the area of the horizontal reinforcement used in the bed joints.

The investigators have specifically restricted the scope of the proposed future research to static loading. A clear understanding of the static load transfer in a composite wall must first be gained before it would be possible to understand the cyclic load behavior. It is obvious that the walls will develop cracks and degrade when subjected to cyclic loads that are much lower than the static failure loads (33, 36). However, questions such as the number of cycles at various load levels and the description of the complete cyclic load history (due to earthquake and/or wind loads) must be resolved before any meaningful results can be obtained from a cyclic loading of composite masonry wall panels.

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