Engineering Notes For Design With Concrete Block Masonry

MASONRY CHRONICLES

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In-Place Testing of CMU Walls Another Alternative

Introduction

One of the fundamental assumptions used for the design of masonry is that each component – including block, mortar, and grout – combines to create one homogeneous unit. This assumption is especially important when considering lateral loads and flexural moments in a direction perpendicular to the wall. For most codes, this homogenous condition is assumed to occur as a product of good quality assurance measures, which typically include visual inspection of the block and reinforcement layout, clean and adequate grout spaces, good consolidation practices, and testing of either assembled prisms or individual components by the unit strength method.

For those projects that must conform to the "State Chapters" of the California Building Code, additional testing on the finished masonry member is required to verify in-place compressive strength, and that adequate bond or shear strength has developed between the inside face of the masonry unit shell and the grouted interior.

The following article has been written to share some recent experiences on these supplemental testing requirements particularly as they relate to determining actual in-place shear capacity. It also discusses the development of an alternative on-site testing procedure that was ultimately used to assess the behavior of a typical wall segment where traditional testing procedures yielded unacceptable results.

Overview of Masonry Cores and Shear/ Bond Strength

As mentioned above, projects governed by the "State Chapters" of the CBC require the testing of samples taken from finished masonry components in addition to the testing of sampled materials or prisms taken during wall construction. Specifically, it requires that at least two 6" cores be taken for each 5,000 square feet of floor or wall area with one core tested in compression, while the other core is tested in shear. Samples are generally taken by the special inspection agency 28 days after walls are completed at locations without horizontal or vertical reinforcing. Where tested in shear, samples must achieve a shear-strength of 2.5 2.5 $\sqrt{\ }$ f′c across the section.

Figures 1 and 2 illustrate the typical method of sampling cores and the guillotine apparatus generally used to perform the shear tests. The intent of these tests is to verify that the finished wall can achieve the compression strength assumed during design and that an appropriate couple or moment capacity can be developed between the reinforcing steel and compression face of the block during flexural loading conditions. Note that with the guillotine test, the apparatus loads the specimen in opposing directions at the interface of the shell and grout zone, essentially measuring bond strength across this joint.

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Figure 3 depicts the traditional stress distribution and force couple assumed for the design of concrete or masonry members, where the ultimate strength design approach is used. For this particular example, the assumed compression zone extends past the width of the face shell and engages a portion of the interior grout. Depending upon the quantity of steel reinforcing and block strength, this compression zone may fall entirely within the width of the face shell. In either case, composite action and development of the steel reinforcing can only occur where adequate resistance to shear flow occurs between the inside face of the block and grout. This requirement for bond is similar to that of adjacent wood sections in glue laminated beams or the use of headed anchor studs to create composite action across the interface of a steel beam and concrete on metal deck. For the case of a masonry member, the critical section is the natural joint at the face-shell grout interface as noted in Figure 3.

Deciphering Poor Test Results

While the core tests required by California State Amendments provide a good indication of wall integrity, the method of sampling and their results are often the subject of some uncertainty. For example, one half of all cores taken through the wall surface are ultimately tested for compression in a direction perpendicular to actual field conditions and would appear to neglect the individual compressive strain characteristics of the block, mortar and grout.

Where initial test results in compression prove to be unacceptable, another alternative may be to saw cut one or two full block course out of the existing wall and test it in compression. Although somewhat more time consuming and destructive, this approach yields a sample that better represents actual field conditions.

Cores taken through walls can also be compromised during the extraction process due to dull blades, improper setup or excessive vibration in the coring machine. All of these factors could compromise the samples and are most significant where the samples are eventually tested in shear. Where initial tests results are poor, these factors should be investigated and corrected for any subsequent testing.

Poor Results and Additional Testing

Where initial test procedures produce unacceptable test results, additional testing is often required. Since no specific guidance is given within the California Building Code for this re-testing, the Engineer of Record and the Governing Agency must exercise some judgment.

Similar to the procedure used to investigate low concrete strength, and as specified in Chapter 19 of the CBC, supplemental testing could include three additional masonry cores taken at areas adjacent to any location with poor initial test results. As a general rule of thumb, the test values are often combined and results noted as acceptable if the average of these tests are greater than the required compression or shear strength and if no single test capacity falls below 75% of the specified value.

Where tests continue to be poor, other alternatives may be investigated. Where inadequate shear capacities are the problem, one option could include the re-evaluation of the block wall neglecting the contribution of the face shell under flexural loads and possibly assuming some degree of fixity at either the footing or subsequent floors. A more costly option could be to provide an external buttress system to limited flexural moments within the wall. Where these options do not work or are too disruptive, the engineer may want to consider an in-place testing method as described below.

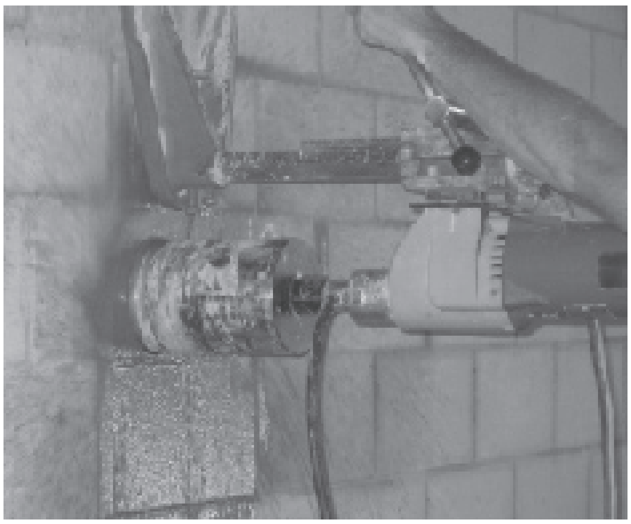

Figure 1
Coring for Wall Sample

Figure 2
Testing with Guillotine Apparatus

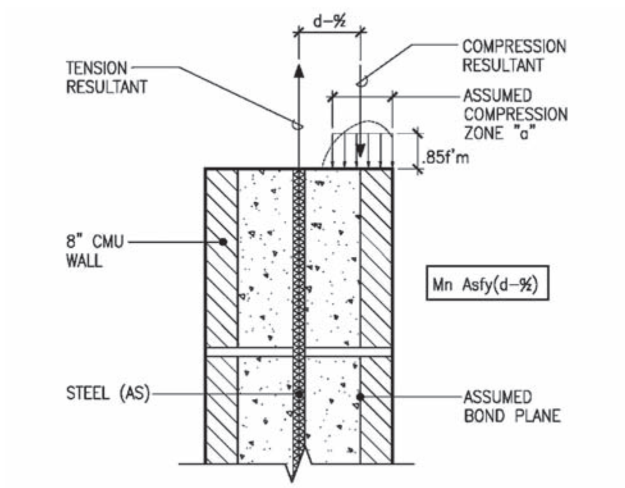

Figure 3
Assumed Stress Distribution and Force Couple

On-Site Testing-Case Study

As noted above, it is not uncommon to have several cores that exhibit poor grout-to-face shell bonds during testing or samples where the face shell completely separates during extraction. Some publications actually suggest that this percentage may be up to 33% for all samples taken. This percentage may include those samples where the face shells separate during extraction and those with low shear results when tested. The question becomes, when is this percentage excessive and an indicator that the block-grout bond may have been compromised due to poor grout quality, excessive material shrinkage or poor consolidation?

On one recent project, initial failure rates due to either low shear test results or complete face shell separation during the extraction process were approximately 47%. Areas exhibiting poor test results were then re-tested with a minimum of three carefully extracted cores and the results averaged. Unfortunately, failure rates remained close to 33% with many samples continuing to experience a complete face shell separation during the extraction process.

Based upon the results, it became obvious that the grout had failed to adequately bond to the CMU at many locations raising concern over the wall's ability to adequately carry future flexural loads. Interestingly, virtually every core tested in compression exhibited acceptable strength when compared to expected values. Shear test results were also consistently poor on one particular side of a wall versus the other and generally exhibited very high values on the opposite face. This phenomenon occurred consistently throughout virtually every building constructed during the same time period and prompted a great degree of speculation. Suggestions for this condition included greater sun exposure on one side of the wall versus the other, the effects of hot weather, poor consolidation, excessive mix shrinkage, poor water quality, and the possible adverse effects of the admixture, which was required to reduce early water loss and to provide expansive action to counteract initial mix shrinkage.

Data Examination

Although the high degree of poor test results clearly indicated that a less than desirable bond had occurred between the inside face of CMU and the grouted interior, the degree to which this poor bonding affected the overall flexural capacity was not fully known. It was recognized that core samples taken at isolated locations account for only a miniscule fraction of the total bond area that would be engaged under flexural loading conditions and that significant bonding at only some areas would most likely be sufficient to create full composite action and development of the reinforcing steel. It was also noted that the natural extension of the web across this possible weakened plane also aided in the flexural development of the entire wall section, although initial calculations indicated that the capacity was not entirely sufficient. Under flexural deformations, it also seemed reasonable to assume that some degree of aggregate interlocking would occur, also aiding the development of the composite section.

Regardless of the suspicions that the walls might perform favorably, the high rate of failed tests together with the fact that these poor results were generally present on one side, could not be ignored. After extensive evaluation of all data, the position taken by the EOR was that the walls must be tested by a different procedure so that the actual flexural strength under field conditions could be determined.

Evaluation Intent/Goals

Once an in place testing was agreed upon by all parties, a protocol document was developed so that the intent and applicability of the testing procedure could be reviewed by all parties. As a guideline, this protocol document was written to be in general conformance with ASTM E 72-98 "Standard Test Methods of Conducting Strength Tests of Panels for Building Construction."

The basic goal of the test was to capture the actual load-deflection characteristics of the wall under incremental static loading. Of particular interest, was the development of a load-deflection curve, where distinct limit states such as the cracking, yield, and ultimate moment capacities could be plotted and compared to expected values based upon assumptions of full composite action.

Since these walls were part of the lateral-force resisting system, the ability of sections to continue to carry full moment capacity at large displacement was also of interest. As such, good wall ductility was another criteria required for acceptable wall performance.

Test Specimen

Due to the time and expense involved for the proposed testing process, a single wall was chosen for evaluation purposes. The wall chosen was adjacent to several locations where at least 5 previous test cores had indicated unacceptable face shell grout bond properties. The direction of loading for the wall was also chosen such that the side experiencing all unacceptable test results would be subject to compression during loading.

To simplify evaluation of the final data, it became clear that the fixity both at the wall base and second floor level would significantly stiffen the wall and make evaluation and comparison of distinct limit states more difficult. As such, it was decided to physically separate a section of wall on all four sides and construct an apparatus that would develop an almost perfect-pinned condition at both the top and bottom of the wall.

Figure 4 below illustrates a section of the wall tested. Actual test results for mortar, block and grout were also reviewed to ensure these assumed material strengths were reasonable. A pacometer was also used to verify reinforcing layout was as expected. Material properties assumed for the wall are also listed below:

$f'm$= 1,500 psi
Es= 29,000 ksi
Em = 1,125 ksi
$f'y$ = 60,000 psi
Mortar: Type S (1,900 psi)
Grout: 2,000 psi.

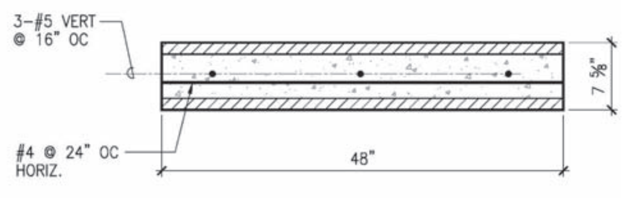

Figure 4
Test Specimen

Test Apparatus

The test apparatus used to support and load the wall consisted of a pair of vertical frames constructed from steel wide flange beams, tube sections, and channels. The frame was designed with significant stiffness and utilized both slip-critical bolted or welded connections to ensure that relative deflection within the fame was not significant. A timber wall was also included at the back of the apparatus to support the air bag used for loading.

Figures 5 and 6 illustrate the supports used at the top and bottom of the wall. The top connection was designed to allow rotation, as well as accommodate vertical slip. The bottom connection was also designed to allow rotation, but was restrained vertically and carried the complete weight of the wall. Once the test assembly was fully constructed and the bottom connection completely intact, a 2-inch section was cut away from the bottom of the wall. This ensured that the wall was completely supported at the bottom bracket and allowed free rotation.

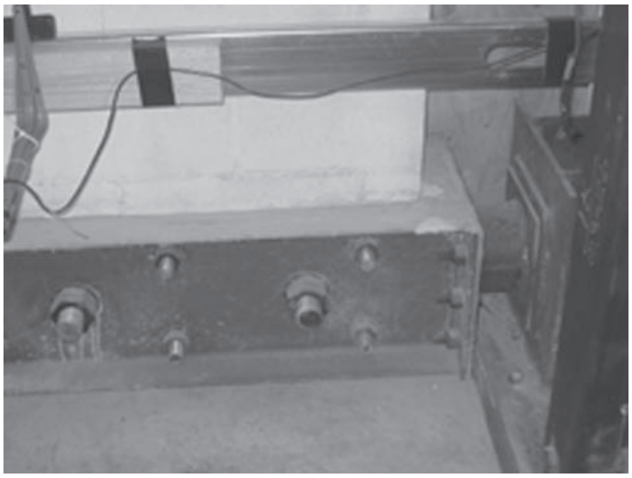

Figure 5
Connection at Base of Test Specimen

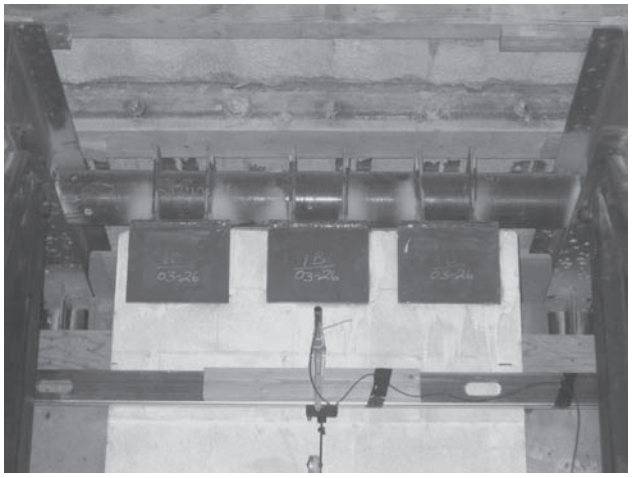

Figure 6
Connection at Top of Test Specimen

Test Instrumentation, Loading, and Observations

The test was conducted on site with the assistance of a qualified special inspection agency experienced with similar tests conducted within a lab environment. After the frame was in place, the wall was loaded with a 4’ x 8’ air bag in accordance with ASTM E 72-02, so that a uniform pressure was achieved over a portion of the wall. This produced a pattern of loading that was close to expected under seismic conditions and one that was reasonably achieved under field conditions. One major goal was to apply a pattern of load that could be easily equated to applied moments with each change in wall pressure.

<u>Instrumentation</u>
Horizontal out-of-plane deflection of the wall was measured at the top, bottom and midpoint mid-height of the wall by use of LVDT (Linear Variable Differential Transformer) devices. Manual gages were also placed at the mid-height of the wall to provide an additional check. Data will be instantaneously captured by a data acquisition system. All gages were capable of measuring horizontal deflections to within 0.01 inch (0.25 mm) and were supported independently from the test frame and the wall to ensure that actual wall deflections were appropriately captured. Pressure within the air bag was measured by a manometer.

A Data Acquisition System (DAS) was used to collect and store instantaneous input and output data. Input data is the applied uniformly distributed load (pressure) and output is the deflections. The advantage of a DAS was that the data was stored without mechanical means and that the graph could be plotted during the course of the testing.

<u>Loading</u>
Out-of-plane loading of the wall panel specimen was achieved by pressurizing a rubberized airbag in contact with the face of the wall in increments of .05 psi (7.2 psf). Displacements and corresponding loads were automatically recorded in equal time increments up to the end of the test.

Since the air bag could not cover the entire height of the wall, simple formulas were developed to equate applied loading with corresponding internal moments and shear forces based upon simply supported beam theory and partial uniform loading. Figure 7 below indicated this relationship. These formulas were used to convert applied pressure into approximate wall moments so that they could be plotted against wall displacements.

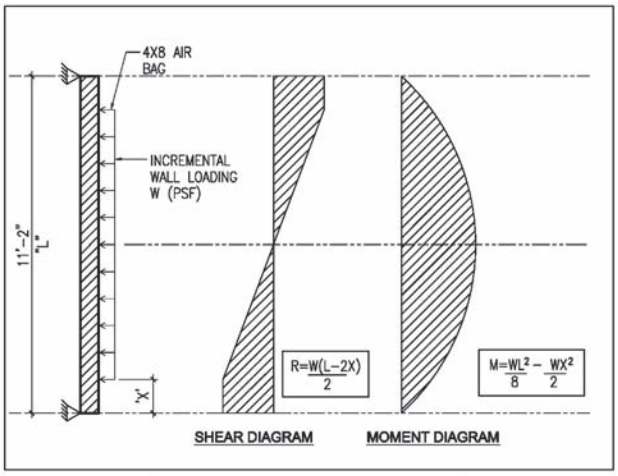

Figure 7
Simplified Shear and Moment Diagram

<u>Other Test Observations</u>
Crack and distress patterns on the backside of the test wall panel were also noted and recorded at periodic loading increments. The side in contact with the airbag was also examined at several stages during the test and after the test was completed to note any cracks or spalling. Upon completion of the test, final observations were made, which included all visible crack patterns, the approximate airbag contact area and residual wall deflections taken up to a week after the test was completed. Exact reinforcing layout was also confirmed by destructive methods.

Test Results/Discussion

As previously noted, the basic goal of the test was to capture the actual load-deflection characteristics of the wall under incremental static loading and compare these results to those that would be expected based upon general engineering principals, assuming a full composite section. Of particular interest, was the comparison of cracking, yield, and ultimate moment capacities, as well as overall wall ductility. Attention was also given to any indication of any premature bond slip between the face shell and the grouted interior and to all cracking patterns which developed.

<u>Comparison of load-Deflection Data</u>
Actual load-Deflection data for the wall tested is presented below in Figure 8 and consists of a plot of “Recorded Mid-Height Displacement Data” and “Effective Mid-Height Displacement Data.” The second plot is provided to account for the decreasing contact area between the air bag and the back of the wall, which became noticeable after about 2” of recorded deflection. This second plot has been interpolated from the original data based upon measurements of the actual bag contact area during the test.

Within this same graph, three simplified plots are also presented for hypothetical walls with composite design strengths that vary from 1500 psi (original design strength) to 3500 psi. These simplified plots were developed based upon general moment-curvature relationships as indicated below in Table 1, and converted to load (psf) versus deflection data by the formulas previously presented in figure 7.

Comparison of the actual wall data and the three curves clearly indicate good flexural wall performance in spite of the unacceptable shear test results previously reported by conventional tests. In fact, up to the theoretical yield moment, results for the "Effective Mid-Height Displacement" are remarkably close to those results predicted for a wall with a design-strength of 2500 psi. Above this theoretical yield point, the tested wall continues to exhibit excellent flexural resistance with its ultimate capacity approximately 10% higher than that predicted by the same curve. This increase in ultimate moment capacity is probably due to higher compressive strengths in the CMU block, an increased slope in the assumed steel strain-hardening profile and ultimate strength, or slight inaccuracies in measuring the effective contact area of the air bag.

Wall Displacements and Ductility

At a mid-height deflection of approximately 6", the LVDT devices used in conjunction with the data acquisition system became inoperable. Beyond this point, data was collected by means of the manual dial gages and were confirmed by physical hand measurement taken relative to the adjacent CMU wall. The test was continued to a final wall displacement of approximately 9" and was then terminated due to the possibility of damage to the testing equipment. This produced a displacement ductility of approximately 7.9, which was better than expected.

At the conclusion of the test, the air bag was completely removed from back of the specimen and the compression face was completely examined. This visual observation yielded no signs of spalling, suggesting that the wall may have been able to achieve an even higher displacement ductility. Observations were also made during the test on the back of the wall where the air bag began to pull away from the edges. No indications of cracking or spalling were present, also suggesting that the effects of the air bag contributing to confinement were negligible at the displacements achieved.

Table 1-Numerical Results

	Effective Data	1500 psi	2500 psi	3500 psi
Mcr Δcr	102,176 .040"	72,057 .067"	93,025 .052"	110,069 .044"
My Δy	212,850 (6) 1.15"	226,175 1.51"	242,074 1.24"	248,887 1.15"
Mu Δu εsu εmu	283,800 9.125" NA NA	227,614 5.32" .007 .003	250,476 6.91" .011 .003	266,715 9.37" .016 .003

NOTES:

1. Mcr, My, Mu- Cracking, yield, Ultimate Moments (inch-#)
2. Δcr, Δy, Δu- Cracking, yield, Ultimate Deflections (inches)
3. εsu = Computed Steel Strain at Mu
4. εmu = Computed Masonry Strain at Mu
5. εsh = Stain Hardening assumed at .006 and .02 of Es
6. Assume My, Δy at .75 x Mu

Conclusions

Results obtained by the in-place testing program clearly indicated that the wall sampled could achieve flexural capacities and ductilities as good as those calculated by engineering principles despite poor initial shear/bond test results by traditional methods.

In the author's opinion, these results are most-likely due to the natural keying of the block webs across the critical cold joint, as well as the frictional interlocking between the grout and shell face as the wall begins to deform.

It is also the author's opinion that traditional core tests, as specified in the California Building Code, continue to provide useful information on the finished wall construction by examining in-place compressive strength, shear/bond strength, and perhaps most-importantly, a sample which can be visually examined for proper consolidation, possible aggregate segregation or even complete voids.

For this particular project, it is important to note that virtually all tests conducted for in-place compressive strength had acceptable results indicating sufficient grout integrity as placed. Based upon the findings of this investigation and in particular, the favorable load-deflection performance of the wall tested, this association is considered relevant and should probably be considered in conjunction with any poor shear/ bond test results before walls are ultimately rejected and/or re-constructed.

Since the placement of grout generally requires a high slump mix, some grout shrinkage is inevitable and is probably the largest contributor to poor shear-bond test results. To help mitigate this problem and avoid a similar situation, it is the author's opinion that the control of water and proper consolidation, and re-consolidation of grout in a timely manner is essential. For this particular project, the rate of acceptance for specimens tested for shear/bond strength dramatically improved, although not entirely eliminated, where additional care was provided during the consolidation process.

References

1. 1998 California Building Code

2. ASTM E 72-98 "Standard Test Method of Conducting Strength Tests of Panels for Building Construction"

3. Abboud, B.E., "Flexural Behavior of Reinforced Concrete Masonry Walls under Out- of-Plane Monotonic Loads"

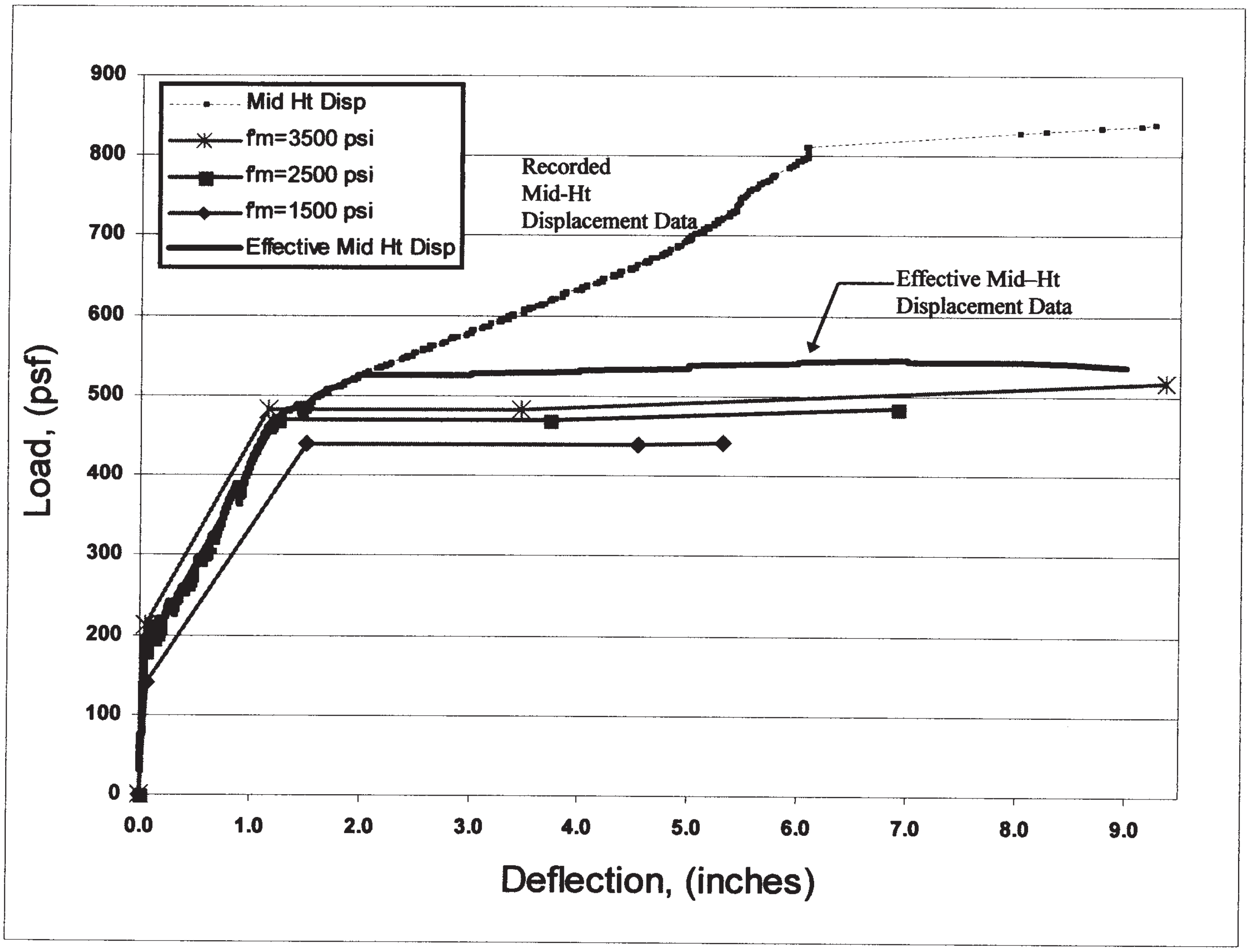

Figure 8
Load vs. Deflection Diagram

This issue of "Masonry Chronicles" was written by Colin Blaney S.E., Principal with the Crosby Group, Redwood City, California.

Enclosed in the envelope with this quarter's "Masonry Chronicles," "CMU Profiles in Architecture" and the "2004-05 Membership and Publications Directory," is a one-page survey for the distribution of informational publications and updates. CMACN would greatly appreciate your participation in this very valuable survey, which will determine how, in the future, we will be distributing publications and informational updates to the engineering community.

This is your opportunity to let us know how we can best deliver your informational needs.

Thank you in advance for taking the time to let us know your thoughts.

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