SHRINKAGE WREAKS HAVOC WITH TENSION STIFFENING IN REINFORCED MASONRY TEST SPECIMENS

P. H. Bischoff [1] , D. Moxon[2]

ABSTRACT

When designing reinforced masonry for strength, the contribution of tension in the masonry is typically neglected and the tensile forces are assumed to be resisted by the steel reinforcement. Although the masonry does not resist tension at a crack, it is still able to carry tension between the cracks through transfer of bond forces between the reinforcement and masonry. This effect is called tension stiffening, and it affects the deformation and stiffness of reinforced masonry elements where part of the element is under tension, such as beams or walls subjected to bending.

This paper describes the results of an experimental programme to investigate tension stiffening of reinforced masonry members under axial load. Half-block specimens six courses high are reinforced with either a single 15M or 20M bar and subjected to uniaxial tension. The load-deformation response of each member is compared with the bare steel response to observe the effects of tension stiffening for reinforced masonry under direct tension. Results are then used to determine the average tensile stress carried by the masonry after cracking (and before yielding of the reinforcing steel), which is compared with the average tensile strength of cracked concrete. This effectively provides a material model for cracked masonry, which can be useful for nonlinear analysis of reinforced masonry structures as well as for assessing serviceability requirements after cracking related to member stiffness, deformation and crack control. Analysis of the test data indicates that tension stiffening in masonry may be comparable to concrete, but results are affected by shrinkage and more work is required to validate this behaviour.

Key words: reinforced masonry, shrinkage, tension stiffening

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INTRODUCTION

When designing reinforced masonry for strength, the contribution of tension in the masonry is typically neglected and the tensile forces are assumed to be resisted by the steel reinforcement only. Although the masonry does not resist tension at a crack, it is still able to carry tension between the cracks through transfer of bond forces between the reinforcement and masonry. This effect is called tension stiffening, and it affects the deformation and stiffness of reinforced masonry elements where part of the element is under tension, such as beams or walls subjected to bending.

Fig. 1 shows a typical load-deformation response of an axially loaded member reinforced with a single reinforcing bar, where tension stiffening represents the difference between the member response and the bare bar response. Similar behaviour is observed for bending, and is often taken into account with an effective moment of inertia. Results from the direct tension test in Fig. 1 can be used to determine the average tensile stresses carried by the masonry after cracking (and before yielding of the reinforcing steel), where the average force in the masonry (N_m) is obtained by subtracting the bare steel load (N_s) from the member response. The tensile stress in the cracked masonry (f_m) then equals N_m/A_m, with A_m being equal to the area of masonry affected by the transfer of bond stresses from the reinforcement. This effectively provides a material model for cracked masonry which is useful for nonlinear analysis of reinforced masonry structures or for carrying out a section analysis of members under flexure, as well as for assessing serviceability requirements after cracking related to member stiffness, deformation and crack control.

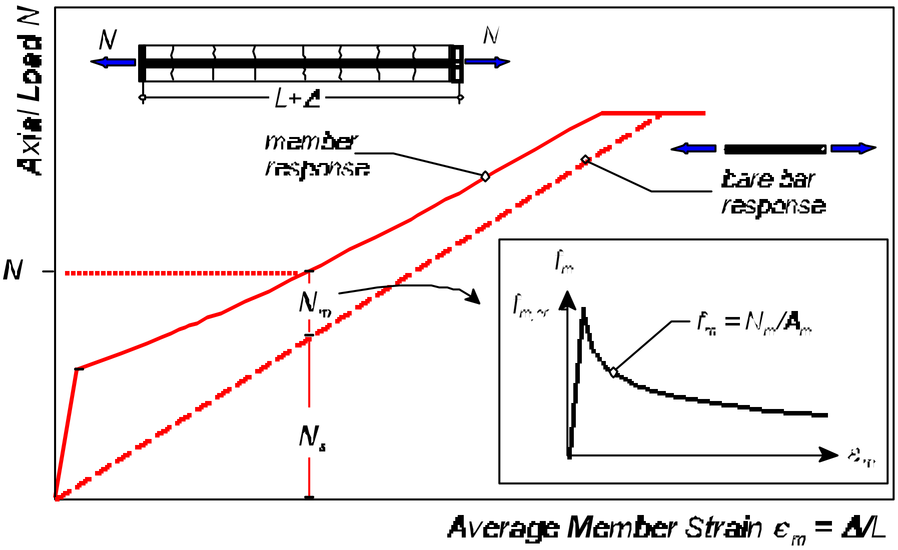

Figure 1. Tension Stiffening of Axial Tension Member

This paper describes the results of an experimental programme to investigate tension stiffening in reinforced masonry members under axial load. Half-block specimens six courses high were reinforced with either a single 15M or 20M bar and subjected to uniaxial tension. The load-deformation response of each member is compared with the bare steel response to observe the effects of tension stiffening for reinforced masonry under direct tension. Shrinkage of the masonry block, mortar, and grout all contribute to initial member shortening, and this has an effect on the member response which leads to an underestimation of tension stiffening unless the bare bar response is offset from the member response (Bischoff 2001). This is particularly important when using this type of test to determine the average tensile stress carried by the masonry after cracking. Shrinkage also results in the development of residual stresses (tension in the masonry and compression in the steel), and the shrinkage in these tests was large enough to cause significant amounts of restrained shrinkage cracking. This led to uncertainty with respect to the amount of shrinkage experienced by each test specimen, and post-cracking stresses in the masonry were only able to be estimated based on an assumed behaviour similar to concrete.

CONSIDERATION OF TENSION STIFFENING IN REINFORCED MASONRY

Tension stiffening is typically not defined explicitly for structural elements made with either reinforced concrete or reinforced masonry, and is often taken into account by using an effective moment of inertia (I_{eff}) for members in bending. Expressions provided for I_{eff} are empirical in nature and limited to both the loading conditions and type of member being tested, as well as the mechanical properties of materials being used in the test member. For example, the expression used to determine the effective moment of inertia when calculating deflection in reinforced concrete beams is affected by the type of reinforcement used, such as fiber reinforced polymer bars which have a lower stiffness than conventional steel bars (Benmokrane et al. 1996). Past tests on reinforced masonry walls (Martens 1996) indicate that tension stiffening plays a greater role in masonry than in reinforced concrete, requiring a model for tension stiffening that is different from the one proposed for concrete.

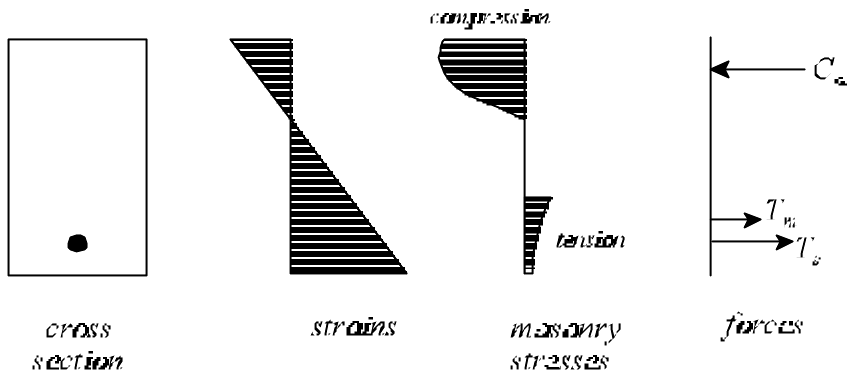

Figure 2. Plain Sections Analysis with Tension Stiffening

Tensile stresses carried by the masonry after cracking represent an average or smeared material property that accounts for the variation of stresses (or forces) along the length of the reinforcement. This type of approach is just a convenient way of obtaining the member load corresponding to a given deformation (Collins and Mitchell 1991). The strength of a member is still governed by the reinforcement which carries all of the tension at the crack, since the masonry does not carry any tensile stresses at the cracks. Hence, member behaviour is affected by tension stiffening up to yielding of the reinforcement, and can be predicted by using a plane sections analysis (see Fig. 2) that includes a concrete or masonry tensile component (T_m) to account for this phenomenon. Other components in the analysis include a compressive force in the masonry (C_m) and an average tension force carried by the reinforcement (T_s). This type of approach can be useful in helping to assess the effective moment of inertia required for analysis of flexural walls subjected to out-of-plane bending (Fig. 3), and can be extended to include an analysis of reinforced elements failing in shear (Collins and Mitchell 1991) as indicated in Fig. 3 for a low-rise shear wall. Tension stiffening is also important in providing appropriate material properties for use in nonlinear analysis of reinforced masonry when smeared finite elements are used.

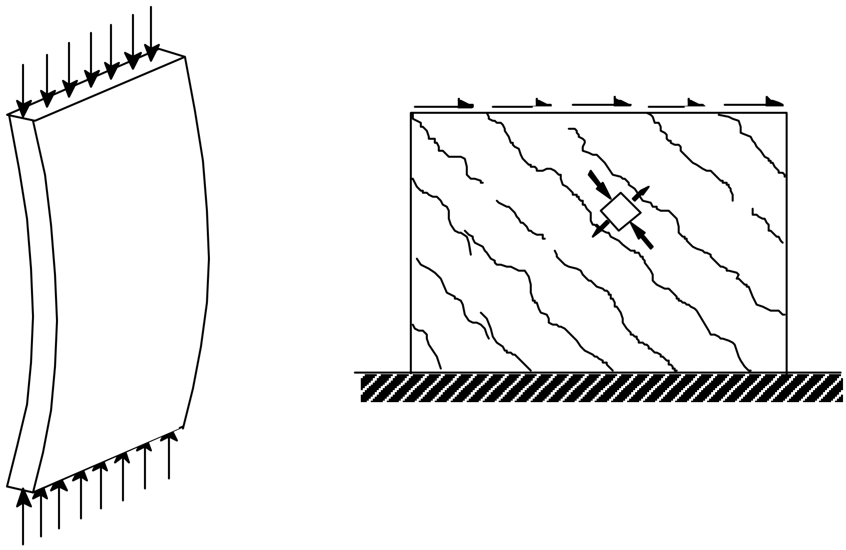

Figure 3. Out-of-Plane Bending and In-Plane Shear Resistance of Walls

FUNDAMENTALS OF TENSION STIFFENING AND SHRINKAGE EFFECTS

Shrinkage of the masonry block, mortar and grout leads to an initial shortening of the masonry member, causing tensile stresses to develop in the masonry when this movement is restrained by the presence of reinforcement. For axial tension members, this effect reduces the member cracking load and can significantly affect tension stiffening results unless the bare bar response is offset from the member response by an appropriate amount as shown in Fig. 4. This offset depends on the amount of shrinkage, and can be determined with an unbonded member (Bischoff 2001) unless significant amounts of shrinkage lead to member cracking before testing begins. Shrinkage cracking reduces the bare bar offset accordingly, as shown in Fig. 5, and an unbonded member which has cracked cannot be used to estimate shrinkage.

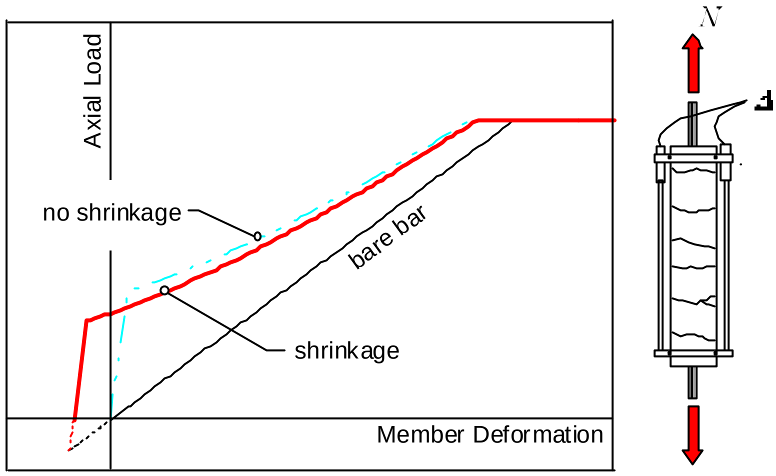

Figure 4. Shrinkage Effect on Tensile Member Response

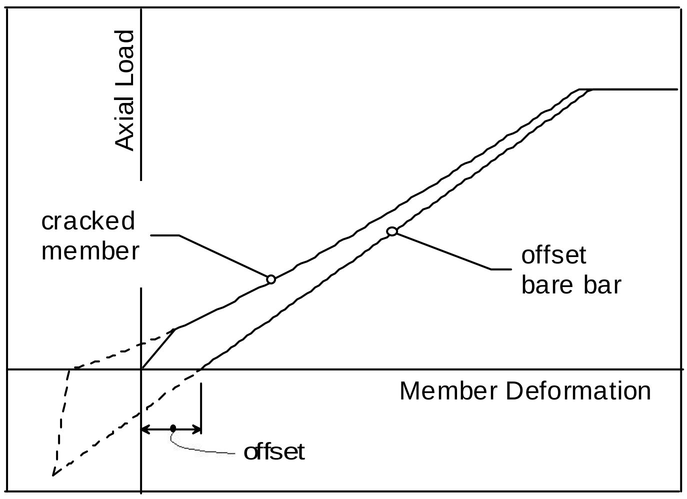

Figure 5. Tension Member with Excessive Shrinkage Causing Cracking

EXPERIMENTAL PROGRAMME AND TEST RESULTS

Testing was carried out on reinforced masonry members under axial tension. Half-block specimens six courses high were reinforced with either a single 15M or 20M reinforcing bar and subjected to uniaxial tension as shown in Figs. 6 and 7. Unbonded specimens (with the reinforcement unbonded over a central length of 600 mm using flexible PVC tubing) were included in the test programme to obtain the bare bar offset. This offset value accounts for shrinkage and is needed to estimate tension stiffening effects properly (Bischoff 2001), but only works well provided that shrinkage does not cause cracking. Specimen details and material properties are provided in Table 1.

Table 1. Test Details and Material Properties

<table>
<tr><th>specimens</th><th>reinforcement</th><th>number tested</th></tr>
<tr><td>Bonded

Unbonded</td><td>15M (D = .68 %)

15M (D = .68 %)</td><td>3

2</td></tr>
<tr><td>Bonded

Unbonded</td><td>20M (D = 1.0 %)

20M (D = 1.0 %)</td><td>3

2</td></tr>
<tr><td colspan="3">Reinforcing Bars 15M: A_s = 200 mm^2, f_y = 489 MPa, E_s = 198.3 GPa
20M: A_s = 300 mm^2, f_y = 451 MPa, E_s = 194.0 GPa</td></tr>
<tr><td colspan="3">Masonry Unit: A_{gross} = 29228 mm^2 , A_{cell} = 10462 mm^2 , A_{net} = 18766 mm^2 (.642A_{gross})</td></tr>
<tr><td colspan="3">Grouted Prism Tests fN_m = 19.0 MPa (2 high prisms), E_m = 16.7 GPa (secant at .33fN_m)
fN_m = 19.9 MPa (3 high prisms), E_m = 17.9 GPa</td></tr>
<tr><td colspan="3">Unit Tests: fN_m = 31.1 MPa (based on net area)
Mortar Tests: fN_m = 40.9 MPa, (from cubes), fN_t = 4.28 MPa (from briquettes)
Grout Tests: fN_g = 25.64 MPa, (from cubes using 4 masonry units and cylinders)</td></tr>
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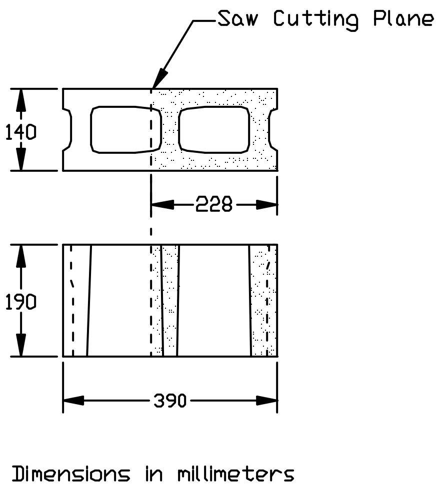

Figure 6. Saw-Cut Concrete Block Details

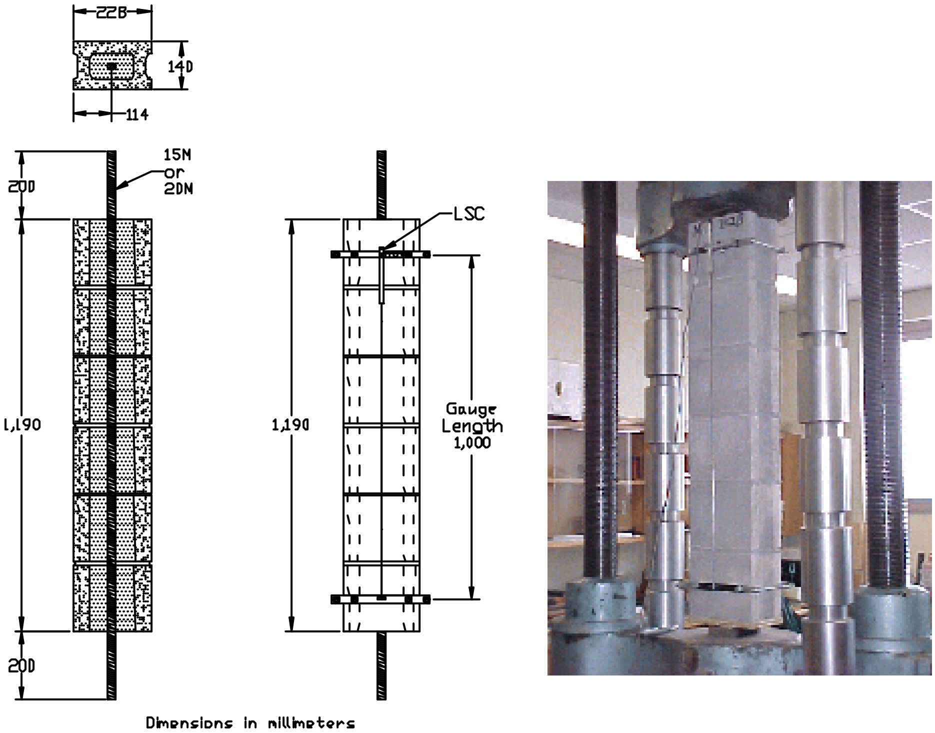

Figure 7. Test Specimen and Setup

Half-block specimens were saw-cut from standard regular stretcher blocks (400x200x150 mm) to provide a section with actual dimensions of 228x190x140 mm as shown in Fig. 6. The blocks had nominal face and web shell thicknesses of 28 mm each, and a slightly non-symmetric cell. Type S ready-mixed mortar was used to construct the masonry block specimens using certified masons. All specimens were constructed vertically with six courses of concrete block, grouted one day after initial set of the mortar, allowed to moist cure (by hosing down under burlap) for 7 days, and then air dried in the lab up to the time of testing (108 and 109 days). Grout proportions were 1 part Type 10 Portland cement, and 2 1/4 parts sand, with a high water-cement ratio to obtain good flowability. Control specimens were fabricated and cured in a similar manner.

Test specimens were loaded in tension using a 900 kN capacity Baldwin testing machine. Average extension of the bonded specimens was measured over a 1000 mm gauge length (extending over 4 blocks) using two displacement transducers placed on opposite sides of the member and attached to mounting frames firmly clamped onto the masonry blocks. Measurements of load and deformation were recorded continuously at 1 second intervals, and plots of load versus average member strain are compared with the bare steel bar response.

Excessive shrinkage in the grout caused cracking in all of the test specimens, except for one unbonded member reinforced with a 15M bar. Hence, results from the unbonded test members could not be used to determine the shrinkage values needed to assess tension stiffening effects properly. For the bonded specimens, members reinforced with 15M bars experienced cracking in up to 2 out of 5 mortar joints before testing, while the 20M specimens exhibited cracking in up to 4 of the 5 mortar joints. Cracking developed in all of the mortar joints during testing. Test results are shown in Fig. 8 for the 15M and 20M bonded specimens, and show the member response crossing over the bare steel response. This clearly indicates that the bare steel response needs to be offset from the member response in order to account for shrinkage, and the amount of this offset will determine how much tension stiffening is observed.

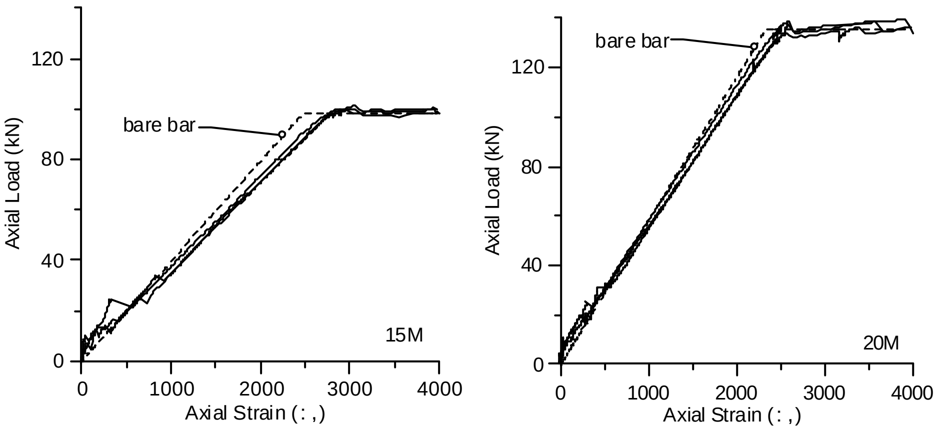

Figure 8. Axial Member Response of 15M and 20M Bonded Specimens

Since shrinkage and the corresponding offset of the bare steel response could not be determined from the unbonded specimens, the specimen response was fitted to an idealized response assuming a shrinkage value of 900 : ,, and a cracking stress in the masonry equal to 1.5 MPa ($0.33\sqrt{f_m}$). These values are found to give behaviour similar to what would be expected for concrete when the response is matched with the yield point of the reinforcing steel, resulting in respective offsets of 412 : , and 249 : , for the 15M and 20M specimens. Shrinkage strains of 900 : , give estimates of tension stiffening which are comparable to concrete. Results shown in Fig. 9 for the 15M and 20M specimens give an indication of the extent of cracking resulting from this restrained shrinkage. The average stress carried by the cracked masonry is obtained by subtracting the bare steel response from the member response, and these results are shown in Fig. 10a for both the 15M and 20M specimens. The good fit with expected values is not surprising, since estimates of shrinkage and the bare bar offset were initially determined by fitting the test response to an idealized member response which was based on having expected average stresses in masonry similar to concrete. Fig. 10b shows the effect that shrinkage has on the post-cracking stress for a 15M specimen, with estimates of shrinkage ranging from 600 : , to 1500 : ,.

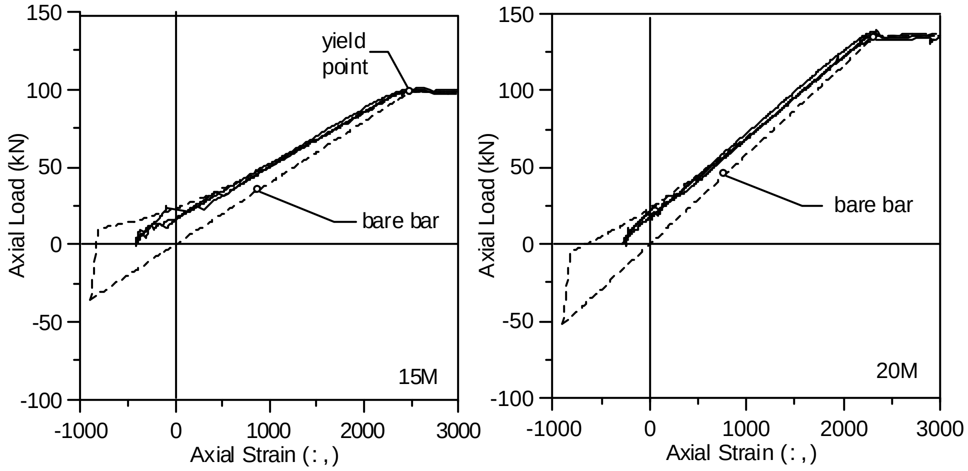

Figure 9. Offset Member Response to Account for Restrained Shrinkage Cracking

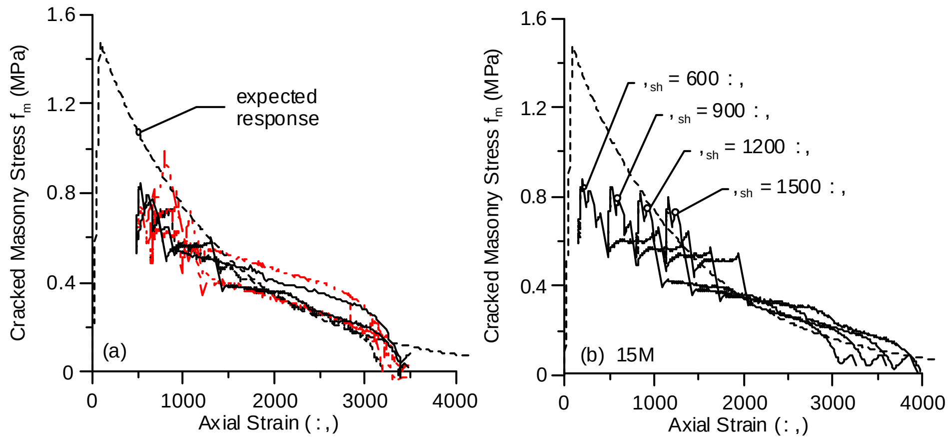

Figure 10. Average Tensile Stress in Masonry after Cracking and Shrinkage Effect

CONCLUDING REMARKS

Tension stiffening does not affect member strength, but is useful for assessing serviceability requirements after cracking related to stiffness, deflection and crack control. It can be used to help evaluate empirical relationships used to predict member behaviour related to tension, such as the effective moment of inertia which is needed for design of reinforced masonry subjected to out of plane bending.

Shrinkage plays a significant role in affecting the tensile member response of test specimens used to measure tension stiffening. Hence, shrinkage strains need to be included in analysis of the member response in order to evaluate tension stiffening properly and to determine the correct average tensile stress carried by the cracked masonry. Excessive shrinkage in the grout used to fill the masonry cells can lead to restrained shrinkage cracking which will affect member behaviour. The test specimens reported in this paper experienced cracking before testing because of excessive shrinkage, and an estimate of shrinkage was required to determine the amount of tension stiffening expected for reinforced masonry. Tension stiffening results appear to be similar to concrete, but are influenced by the estimated shrinkage value. More work is needed in this area and, as a first step, grout with a low water-cement ratio could be used in combination with a plasticizer to minimize shrinkage and eliminate any member cracking before testing.

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