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Numerical analyses of masonry wall behaviour under shrinkage loading

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ABSTRACT : For this contribution, behaviour of masonry wall under shrinkage loading is studied computationally. First, meso-analyses of masonry wall parts are performed to obtain macroscopic constitutive behaviour. Subsequently macro-analyses of base-restrained shrinking masonry walls are performed to study the response of the wall under this loading condition. Sensitivity of masonry wall to material model parameters is also investigated. The results reveal the influence of shrinkage loading on pattern of cracking in masonry wall and how material parameters affect masonry behaviour in terms of composite strength and toughness, as well as crack initiation and crack propagation.

KEYWORDS : Finite element method, Non-linear inelastic analysis, Masonry wall, Shrinkage, Cracking

1. INTRODUCTION

Cracking induced by shrinkage in masonry walls is an often-encountered aesthetic problem in the Netherlands. Despite the negligible impact to structural requirement, observed architectural performance can be highly impaired [3]. Hence, there is a strong need for designers and also manufacturers to have proper guidelines and clearer insight in this matter. The omission of a movement joint has led to the cracking and eventual separation of the wall at the location of the primary crack shown in Figure 1.

Semi-analytical rules have been proposed [2,4,5], to design movement joints for walls without openings. These analytical rules are based on the linear elastic stress distribution in walls. Furthermore, these rules employ strength-based criteria, requiring that a certain average tensile stress in the wall should not exceed a strength limit. Such a criterion does not consider fracture mechanics and fails to provide the in-depth understanding of this complex phenomenon. Another serious shortcoming of these existing design rules is that no indication of crack width can be given.

To fill in this gap, a numerical approach, based on fracture mechanics has been recently proposed and proved to be a better alternative [6]. The strategy adopts a two-level technique of (1) a meso-analysis to derive the constitutive law for an equivalent macro model, and (2) a macro-analysis to predict the maximum crack-width in the structure. By such a simplified modelling strategy, crack initiation and evolution can be pragmatically captured and with a formalism of a non-linear finite element method, repetitive analyses of shrinking walls become viable within this concept. From the results, rules for movement joint spacing can be derived.

Realising that different masonry types possess different fracture properties, the overview of shrinkage-resistant capability is an important concern not only for manufacturers but also designers in order to develop and choose the proper products for specific sites and environmental conditions. In this paper, the two-level computational approach is adopted to perform parametric studies of restrained shrinking masonry walls, built of certain categories of Dutch Calcium Silicate masonry units. In particular, the influence of the unit size on masonry composite strength and toughness is investigated, and in turn, its influence on the shrinkage behaviour of large walls. All the analyses are performed with the multi-purpose finite element program DIANA [1].

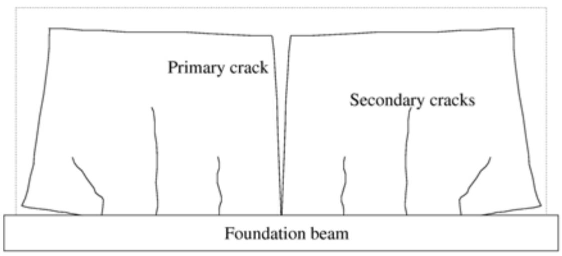


Figure 1. General crack pattern in base-restrained shrinking wall [7]

2. MODELLING APPROACH

A two-level technique is used to simulate the shrinkage response of a base-restrained masonry wall. First, a meso-analysis of a representative wall part under conditions, which reasonably imitate those in the actual area of the primary crack in a large wall, is performed. This is schematised in Figure 2. From the results, a constitutive law is derived for the masonry composite, which is subsequently employed as the constitutive behaviour of an equivalent vertical crack on the macro scale. This second level schematisation is illustrated in Figure 3.

2.1 Meso-analysis

To characterise the equivalent vertical crack for the simplified macro-analysis in Figure 3, an appropriate constitutive law is sought for the interface elements, which represent the crack. It is shown that for a homogeneous representation of the wall, the principal stresses are horizontal in the central area, where the primary crack is expected [6]. Therefore, the response of a representative wall part under uniaxial tension should be derived to represent the behaviour of the wall in the vicinity of the primary crack. For this purpose, a periodic wall part is analysed by a discrete modelling approach [6]. The interface elements employed in this meso-analysis obey an interface material model capable of simulating fracture, crushing and shear-slipping, including shearing dilatancy [7]. Figure 2 illustrates the characterisation process. The periodic part is analysed to determine its deformational response. The elastic response is then attributed to the masonry away from the crack, which is considered to be homogeneous. By subtracting the elastic deformation from the total deformation, the total cracking deformation is found, which defines the constitutive behaviour of an equivalent mode I crack in the simplified macro-model. In this manner equal global deformational behaviour can be predicted by the detailed model and the equivalent vertical crack model shown in Figure 2.

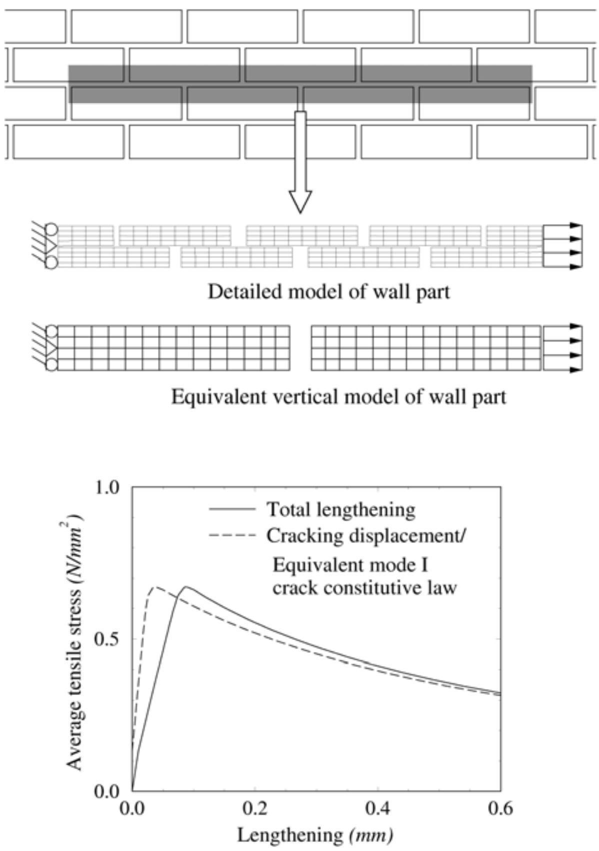


Figure 2. Wall part *meso*-analysis for the derivation of crack constitutive behaviour, to be employed as equivalent vertical crack constitutive law in *macro*-analysis [7]

The important issues, which should be captured with reasonable accuracy in this characterisation process, are the loading conditions (uniaxial tension), the failure mechanism and the level of confinement, as is comprehensively described in [7].

2.2 Macro-analysis

In the macro-analyses, the equivalent vertical crack concept shown in Figure 2 is employed for the large masonry walls. The uncracked continuum is idealised to behave linear elastically and fracture is localised in a potential crack at the center of the wall. The same simplified shrinkage and thermal strain evolutions are assumed as by the analysts [2, 4, 5]. This entails a combined hygral and thermal shrinkage, which is spatially uniform, isotropic and increases linearly in time. After initially activating self-weight in the model, the shrinkage is activated in the masonry wall. As for steering non-linear analysis, incremental process is conducted by controlling time step with Newton-Raphson iterative procedure.

In the finite element model, the elastic continua of masonry and the concrete foundation beam are represented by eight-noded quadrilateral plane-stress elements with a 3x3 Gauss integration scheme. Six-noded interface elements with a Lobatto integration scheme are adopted for the potential vertical crack, as well as for the interface between the wall and the foundation. Slipping along the wall/base interface is not included for lack of experimental data, but also to demonstrate the worst-case scenario. The continuum away from the central, primary crack is assumed to behave linear elastically. The effect of bulk creep is ignored for simplicity. As explained in [7], this gives a base-restrained shrinkage response, which is on the safe side. The homogenised response of the equivalent vertical crack model was confirmed to satisfactorily match with that derived by the meso-level detailed model and in the extreme situation to provide the more conservative results.

This allows the present investigation to focus directly on the effect of the vertical crack parameters on the global deformation capability of base-restrained shrinking masonry wall.

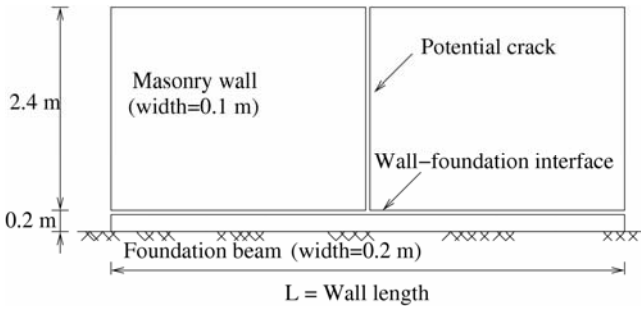


Figure 3. Simplified equivalent macro wall model

3. CRACK CONSTITUTIVE LAW: MESO ANALYSIS

For the unit size sensitivity analyses as outlined in section 2.1, certain Dutch Calcium Silicate masonry products are studied. For simplicity and to concentrate on the influence of the unit geometry, it is assumed that the various units have equal material properties, despite evidence otherwise.

The subjective classes of masonry products are (a) brick type units (214×55×100) with 10 mm mortar joints, (b) block type units (440×300×100) with 10 mm mortar joints, (c) block type units (440×300×100) with 2 mm glued bed joints and 3 mm glued head joints and (d) element type units (900×600×100) with 2 mm glued bed joints and 3 mm glued head joints. Tables 1 and 2 summarise the meso-level properties.

Based on the meso-analysis of wall parts under tension, we obtain the average tensile stress-crack width relation. As an example, Figure 4 shows the meso-analysis results of masonry class (b). The total load deformational response is shown, together with the deformed specimen at three stages of loading. In this case all head joints crack open, followed by unit fracture. From the global load-deformation behaviour the average stress is derived by deviding the load by the total cross-sectional area. By subtracting the elastic deformation from the total lengthening to derive the total crack width, the crack constitutive law derivation is completed. In Figure 5, the crack constitutive laws for all the simulated products are shown and treated as the basis of material model parameters for the equivalent vertical crack in subsequent macro analysis.

Table 1. Parameter for potential Element/Block/Brick crack

Element/Block/Brick	
Tensile strength (N/mm^2)	Tensile fracture energy (N/mm)
1.0	0.060

Table 2. Parameter for head and bed joints in meso-analysis

Head and bed joint		
Parameter	Bond type	
	Glue	Mortar
Tensile strength (N/mm^2)	0.4	0.2
Tensile fracture energy (N/mm)	0.040	0.004
Original adhesion (N/mm^2)	0.8	0.4
Shear fracture energy (N/mm)	0.04-0.03 σ	0.02-0.03σ
Initial friction angle ($^\circ$)	36	36
Initial dilatancy angle ($^\circ$)	31	31

Note: σ is normal confining pressure with positive sign for tension and negative sign for compression.

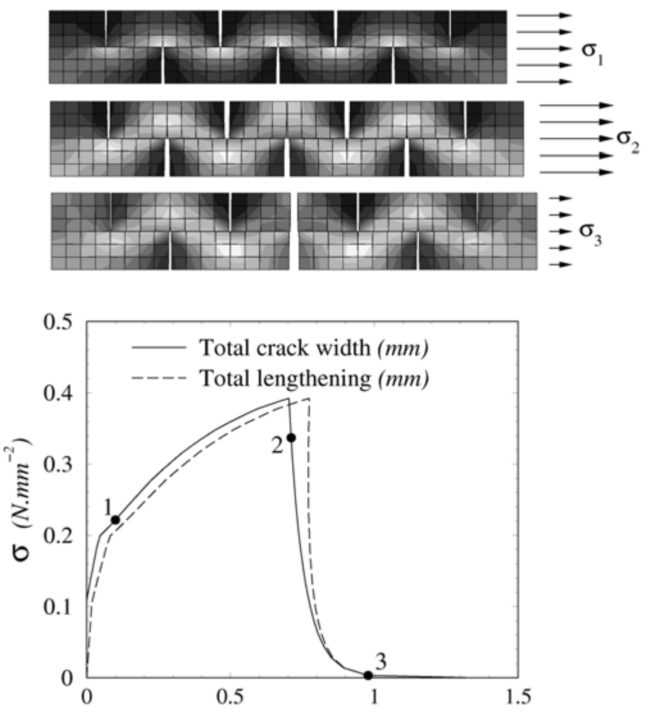


Figure 4. Typical derivation of the equivalent vertical crack constitutive behaviour.

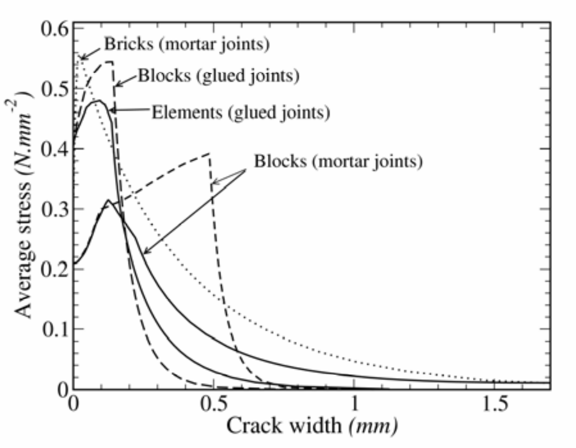


Figure 5. Constitutive behaviour for various calcium silicate masonry types, to be employed for the equivalent central crack in simplified restrained shrinking wall analyses.

4. RESTRAINED SHRINKAGE: MACRO ANALYSIS

In this section macro analyses are performed along the lines described in section 2.2 to study the sensitivity of base-restrained wall shrinkage response to fracture properties induced by unit size effects. In addition, the effect of E-modulus, wall length and foundation may be studied. For these analyses, equivalent primary crack constitutive laws are employed, based on the material laws obtained from the meso-analyses in the previous section. A series of macro material parameter variations have been set up, as summarised in Table 3 and 4.

Table 3. Material parameters employed in macro analysis

Component	Parameter	Value
Masonry	Young's modulus; E	See Table 4
	Poisson's ratio	0.2
	Mass density	1,800 kg/m^3
Concrete beam	Young's modulus	30,000 MPa
	Poisson's ratio	0.2
	Mass density	2,400 kg/m^3
Wall-foundation interface	Normal stiffness	333 N/mm^3
	Shear stiffness	139 N/mm^3
Potential crack	Normal stiffness	10^6 N/mm^3
	Shear stiffness	10^6 N/mm^3
	Tensile strength; f_t	See Table 4
	Tensile fracture Energy; G_f	See Table 4

Table 4. Outline of the material parametric studies in macro-analysis

Test	E (MPa)	f_t (MPa)	G_f (N/mm)	Remark
Wall A	9000	0.4	0.15	Reference
Wall B	9000	0.2	0.15	Low Ft
Wall C	9000	0.6	0.15	High Ft
Wall D	9000	0.4	0.10	Low Gf
Wall E	9000	0.4	0.20	High Gf
Wall F	6000	0.4	0.15	Low E
Wall G	12000	0.4	0.15	High E

4.1 Reference wall A

Firstly, wall A is analysed to serve as an average, reference case. This is to provide an insight into the cracking mechanism at the macro-level. In order to delineate the shrinking wall response, the maximum crack width which arises in the central crack is plotted at each level of shrinkage strain in Figure 6. The deformation patterns, together with associated primary principal stress trajectories at certain stages are plotted in Figure 7. The results indicate that cracking initiates at the bottom when the tensile stress threshold is exceeded there. Subsequently, the crack propagates towards the upper part of wall. Finally, after all fracture energy is dissipated in the central crack, the original wall is split into two separate parts, in which the stress distributions are identical to that in an elastic, base-restrained shrinking wall.

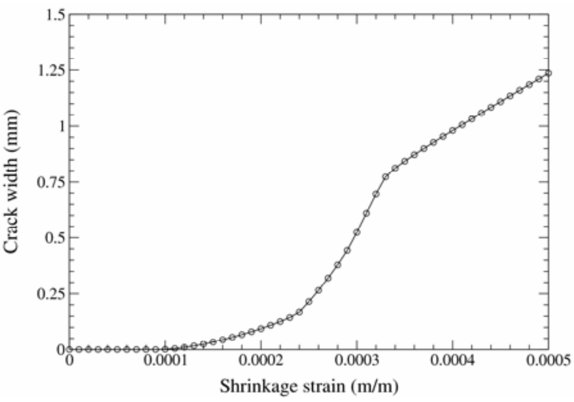
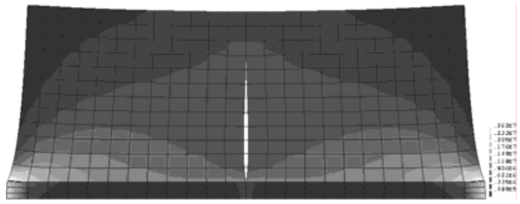
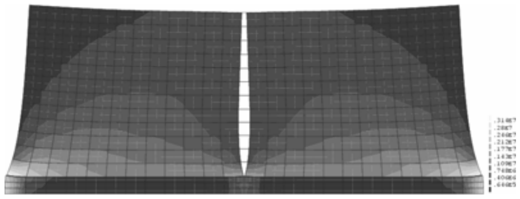


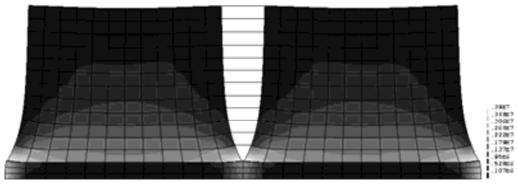
Figure 6. Shrinkage-crack width diagram of reference wall A



a) At shrinkage strain = 0.00020 m/m



b) At shrinkage strain = 0.00025 m/m



c) At shrinkage strain = 0.00035 m/m

Figure 7. Progressive cracking in reference wall A

4.2 Sensitivity to material parameter variation

Variation of the tensile strength affects the maximum crack width-shrinkage strain diagram as shown in Figure 8 for walls A-C. It is seen that the higher tensile strength delays the initiation of cracking in the masonry wall, while the lower strength leads to cracking at a lower shrinkage. As the analysis is extended to a higher level of shrinkage, all the responses tend to fall on the same line (see Figure 9). This can be explained by the fact that at a specific limit point of shrinkage level, all the fracture energy is fully dissipated. After that point the wall is separated into two parts. The subsequent behaviour is elastic and, thus, similar for all cases.

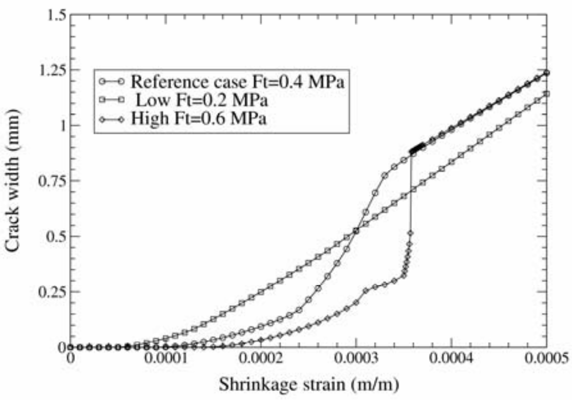


Figure 8. Influence of f_t on the shrinkage crack-width: walls A-C.

The variation of toughness/fracture energy - walls A, D and E - does not affect the crack initiation, but rather the cracking rate, as illustrated in Figure 10. A higher mode I fracture energy leads to ductile behaviour, hence it prolongs the crack propagation to the top part of wall. On the other hand, the lower mode I fracture energy results in a brittle response.

The effect of Young's modulus on the overall cracking resistance of the wall is displayed in Figure 11. With a higher Young's modulus, wall behaviour becomes much stiffer, causing breaching of the stress limit and subsequent cracking at lower strain. On the other hand, with a lower Young's modulus, the wall is much more flexible and deformability is improved.

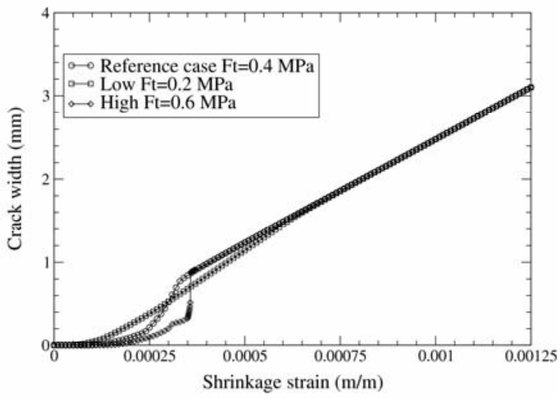


Figure 9. Influence of f_t on the shrinkage-crack width: Extended analysis

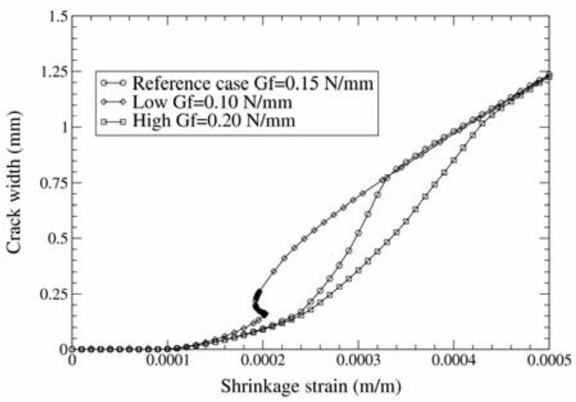


Figure 10. Influence of G_f on the shrinkage-crack width: walls A, D & E.

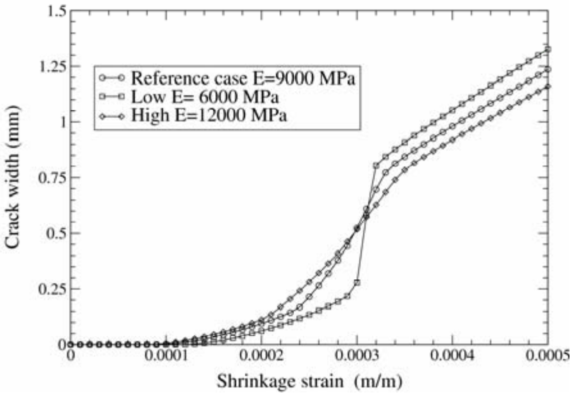


Figure 11. Influence of E on the shrinkage-crack width: walls A, F & G

CONCLUSIONS

The behaviour of masonry wall under shrinkage loading is studied by non-linear finite element analyses. Meso analyses are firstly set up to determine the response of wall part subjected to uniaxial tension. The analyses of this wall part are tested for various calcium silicate unit masonries with both glued and mortar joints. These results provide the basis of material model parameters for the macro analysis. The response of base-restrained shrinking masonry wall at the macro level is simplified by considering only the primary crack and the shrinking wall response is revealed to be sensitive to the composite strength and toughness. Higher strength postpones cracking to higher levels of shrinkage, while higher toughness decreases the cracking rate. It is regarded that the modelling strategy presented in this paper is capable of explaining the evolution and cracking mechanism of masonry wall under shrinkage loading condition. Such concept can be extended for the case of thermal expansion in masonry wall induced by the effect of solar radiation which is a common situation encountered in Thailand and other tropical countries.

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