The variability of tensile and flexural bond strength

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THE VARIABILITY OF TENSILE AND FLEXURAL BOND STRENGTH

Erik van Geel[1] and Rob van der Pluijm[2]

1. ABSTRACT

The flexural bond strength is normally higher than the tensile bond strength. In this paper the influence of some fundamental parameters on this phenomenon is explained. The major part of the paper deals with the influence of the coefficient of variation (COV) of the tensile bond strength on the flexural strength. Normally the COV that occurs with tensile tests on small masonry specimen (e.g. the cross couplet test) is higher than the COV that occurs with 4-point bending tests (4pbt) on wallettes.

The research was carried out in a numerical way, taking non-linear material behaviour into account.

The outcome of the numerical analysis showed that an increase of the length of the crack (=increase of the width of a specimen in a 4pbt) eventually reduces the COV to zero. This kind of behaviour is also found in parallel systems. The found theoretical reduction of the COV with increase of the crack length is larger then is found in experiments. Some possible causes for this discrepancy are presented.

2. INTRODUCTION

The main objective of the numerical research presented in this paper is finding a theoretical relation between the tensile bond strength and its statistical distribution established in tensile tests on small specimen and the flexural bond strength in e.g. 4-point bending tests on wallettes. The non-linear material behaviour under tension is taken into account. Data concerning the non-linear material behaviour of masonry has become available in the national Dutch research program on structural masonry carried out by TU Eindhoven, TNO and TU Delft under the auspices of the Centre for Civil

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The main non-linear phenomenon under tension that is taken into account is *tension softening* [1,2]: when the tensile bond strength is reached in a brick-mortar interface, the tensile stress does not show an immediate drop to zero but a gradual decrease to zero. Due to this tension softening a stress redistribution can take place under flexural loading, leading to a higher flexural bond strength than would be expected from the tensile bond strength. This phenomenon is illustrated in fig. 1.

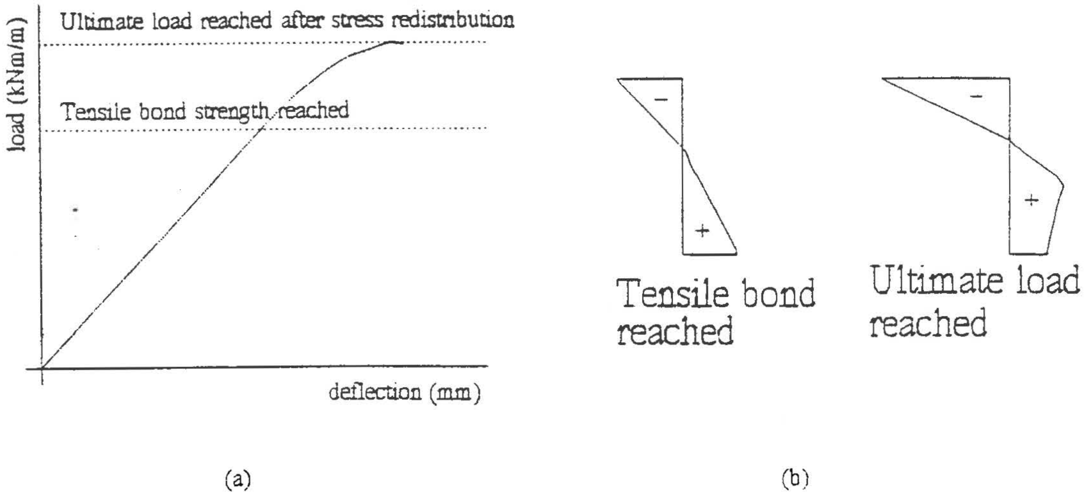


Fig. 1: Typical load-deflection diagram for masonry under flexure (a) and successive stress distributions in the fracturing joint (b)

It was proposed to develop a three-dimensional numerical model in which both the variability of the tensile bond strength and non-linear material behaviour are incorporated. The model would be subjected to a flexural load (momentum) perpendicular to the bed joints. Different bed joint lengths (thus crack lengths) should be considered. The length of the crack parallel to the bed joint has been varied for two reasons:

- a larger crack length increases the chance of the occurrence of low tensile bond strength values,
- the possible redistribution of stresses between adjacent areas with different tensile bond strength may change with increasing crack length.

3. NUMERICAL MODELLING

A three-dimensional finite element model is developed within the DIANA code as depicted in fig. 2. In the model one bed joint is assumed to be decisive for failure, which means that only in this joint non-linear material behaviour is modelled. The model is based on a preliminary study on a two-dimensional model of a 4pbt. From this study it became clear that taking only the non-linear behaviour of one bed joint into account and the reduction of the modelled part of the specimen do not influence the numerical 'test result'. The great advantage of this approach is a considerable decrease of calculation time. The softening model that is used was developed for plain concrete by Hordijk and Reinhardt [3]. This model can also be used for the bond interface between the mortar and the unit [2]. A mesh refinement was applied near the fracture joint to make a spatial distribution of tensile bond strengths possible.

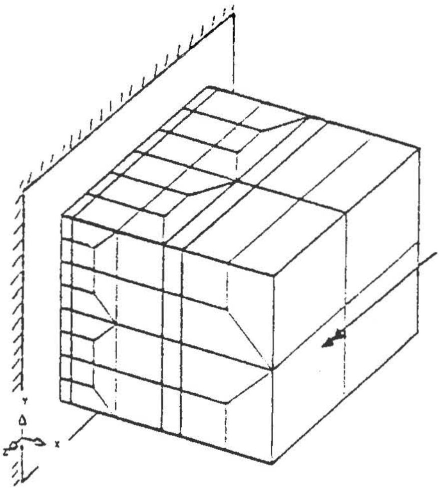


Fig. 2: Three-dimensional Finite Element Model.

For the bricks quadratic continuum elements were used. Bed joints are modelled with quadratic interface elements, representing the combined behaviour of mortar (stiffness) and brick-mortar bond (tensile bond strength and fracture energy). The influence of head joints on flexure perpendicular to the bed joints is neglected completely in this research.

Material properties of brick, mortar and interface are based on tests on several types of bricks and mortar, carried out by Van der Pluijm and Vermeltfoort [2], from which properties are chosen as presented in table I. Under tension, a lower Young's modulus is attributed to the mortar elements than under compression. This difference, observed in uniaxial experiments [2,4], can be explained by assuming contact areas within the bond interface between mortar and unit, being able to transfer compressive stresses but unable to transfer tensile stresses.

Table I: Material properties in finite element analysis

Elements	**Material property**	**Value**
Bricks	Young's modulus E_b	17500 N/mm²
	Poison ratio ν	0.20
Linear joints	Compressive Young's modulus $E_{m,d}$	13000 N/mm²
	Tensile Young's modulus $E_{m,t}$	4500 N/mm²
Non-linear joint	(Mean) tensile bond strength $f_{m,t}$	0.50 N/mm²
	Fracture energy G_f	0.007 N/mm

4. STATISTICAL ASPECTS

High variabilities of material properties are typical for masonry. In the context of the present research, two major questions arise: first, what statistical distribution is able to give an acceptable representation for the tensile bond strength and second, what is a realistic value for the variability? Based on previous research (the most important being described in [5,6,7,8]), the tensile bond strength can be represented with a normal distribution (referred to as K1) with a coefficient of variation (COV) of 25%. The COV represents the ratio between standard deviation σ and mean value μ. A mean value of 0.5 N/mm^2 was chosen (table I).

Random tensile bond strengths were generated for each element, to which tension softening-diagrams were automatically added. This is done by generating one tensile bond strength $f_{tb,i}$ from K1 for areas with the length of a half brick length assuming a running bond pattern. Furthermore it is assumed that, due to the hardening process of mortar, lower tensile bond strengths occur at the outer zone of a joint. This is modelled by taking $f_{tb,i}$ as the mean values μ_i for a normal distribution $K2_i$ for every *half* brick length area with a COV of 10%. After generating the tensile bond strength values for the elements of each half brick length area, the highest values were assigned to the elements in the middle of the half brick length area and the lowest to the outer zone of the area.

An example of the spatial distribution of tensile bond strengths over the bed joint is drawn in fig. 3. In this example the length of the bed joint equals the length of one brick length (i=2).

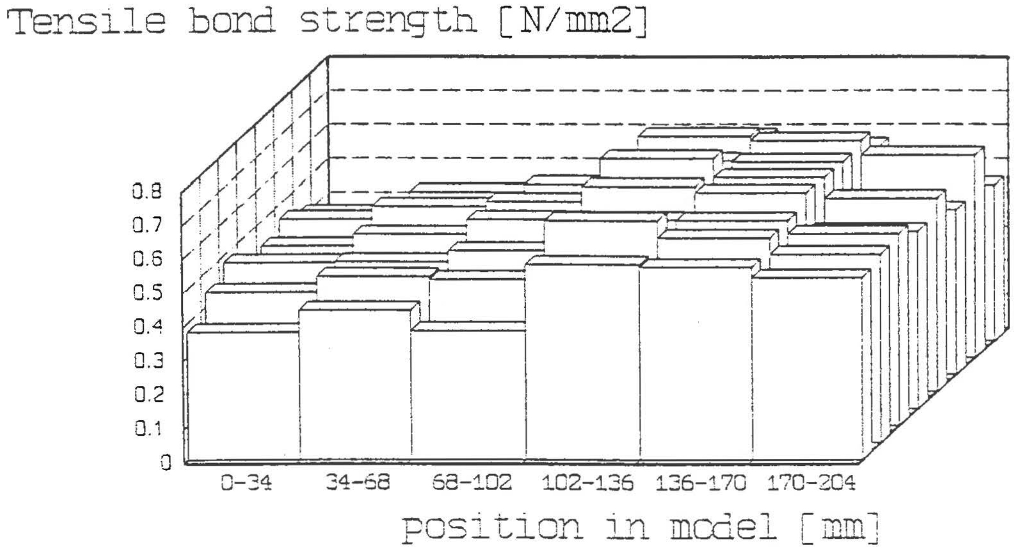


Fig. 3: Example of attributing randomly generated tensile bond strengths to finite elements.

5. NUMERICAL RESULTS

In the numerical research four different bed joint lengths are examined. These lengths are multiples of 102 mm, a half brick length of the chosen brick type: 102, 204, 612 and 1224 mm. The number of calculations carried out with these models are 20, 20, 9 and 6, respectively. In fig. 4 -as an indication- load-deflection curves for the calculations for a model length of 204 mm are presented. Fig. 5 summarises the numerical results of all calculations. In fig. 6 an example is given of crack growth within the decisive bed joint (view perpendicular to flexural stresses, white=uncracked, black=cracked). It is obvious that in this particular calculation the weakest elements are situated on the right side of the model and crack growth gradually expands to the left before reaching the ultimate load.

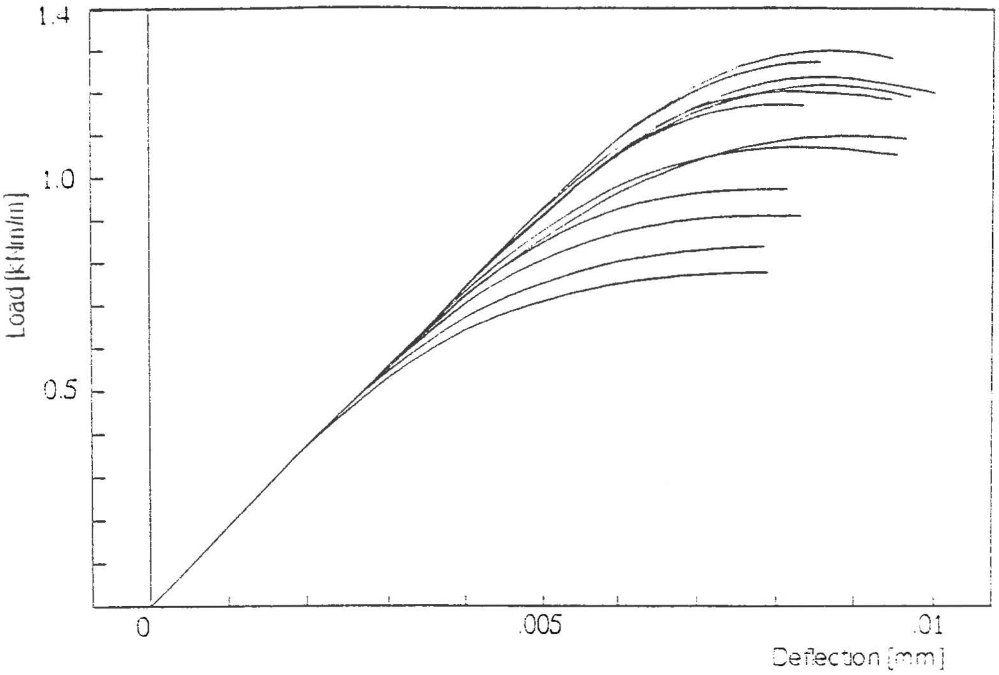


Fig. 4: Load-deflection diagrams calculated for models with length 204 mm.

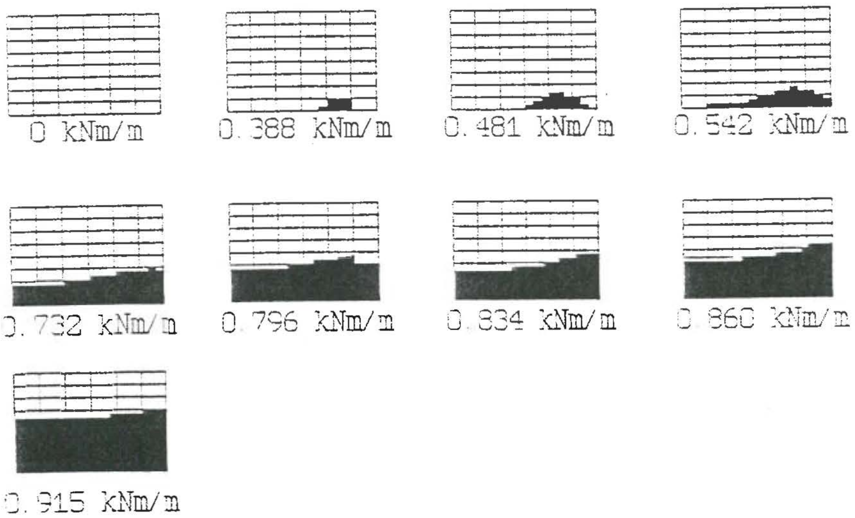
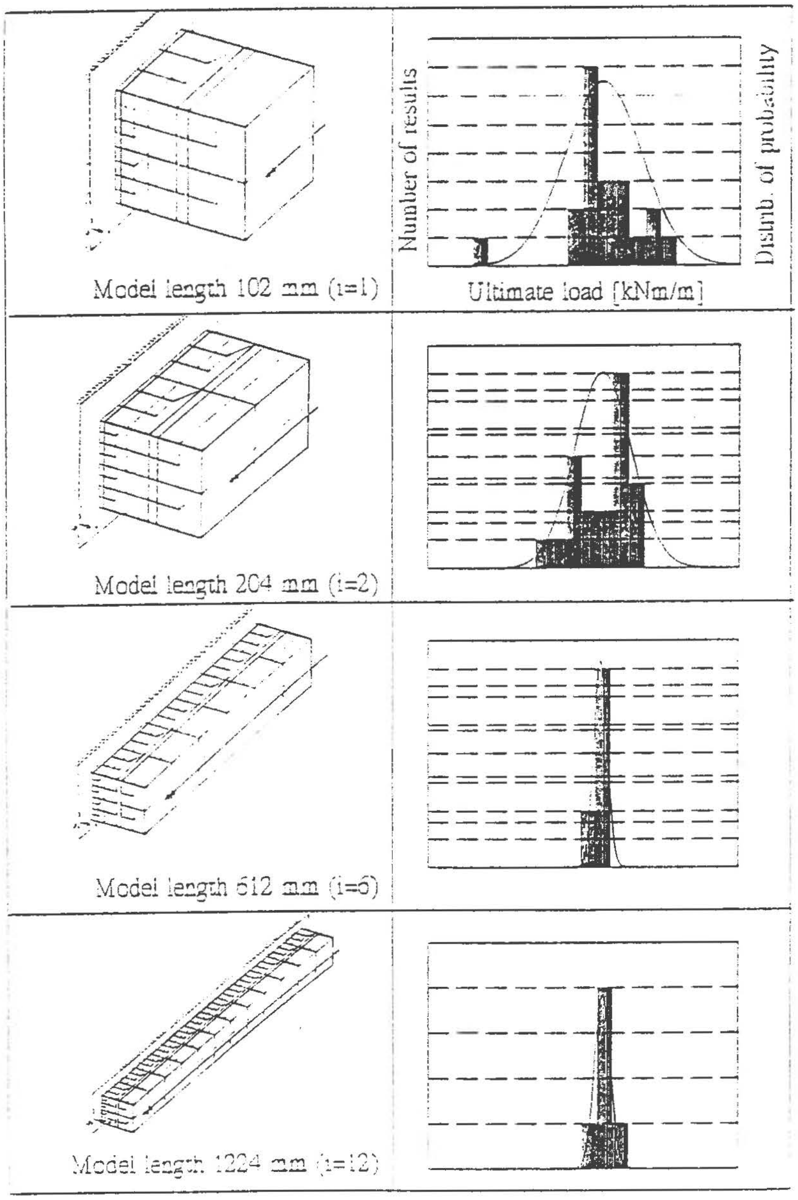

0 kNm/m
0.388 kNm/m
0.481 kNm/m
0.542 kNm/m
0.732 kNm/m
0.796 kNm/m
0.834 kNm/m
0.860 kNm/m
0.915 kNm/m

Fig. 5: Crack growth up to peak load for a model with length 204 mm.

From fig. 6 it can be seen that with increasing model length a sharp decrease of the COV is observed. From the calculations an almost linear relation between the mean tensile bond strength and the flexural strength could be observed. The decrease of the COV with increasing crack length is caused by a combination of the next two phenomena:

- As the length of the model increases (and with this the number of elements in the decisive joint) the statistical distribution of generated tensile bond strengths and the initial distribution K1 are more alike and differences between models become less pronounced than with smaller models.
- The amount of fracture energy is taken equal for all elements. This was done because experiments [1,2] showed a large COV for the fracture energy and no relation with the tensile bond strength. This kind of modelling results in a less steep

descending branch of the stress-displacement-curve when the tensile strength decreases. The less steep descending branch involves that a relative ductile behaviour occurs. In fig. 7 this effect is shown for one model with a uniform increasing strength.



$\mu = 0.71$ N/mm^2
COV = 21.6 %

$\mu = 0.71$ N/mm^2
COV = 16.1 %

$\mu = 0.70$ N/mm^2
COV = 3.9 %

$\mu = 0.71$ N/mm^2
COV = 4.6 %

Fig. 6: Results of the finite element analysis.

The relative ductile behaviour of the weak elements in a model with random values enables the strong elements to develop 90-95% of their full capacity. Together with the first mentioned phenomenon this explains the decrease of the COV in the numerical model. The fact that the strong elements cannot develop their full capacity implies that the mean average flexural bond strength should show a slight decrease with increasing length. This is not evident from the numbers in fig. 6 because of the limited amount of calculations with increasing crack length.

In fig. 8 the post-peak stress-displacement curves and the stress states at peak load are drawn for both a weak ($f_{bt} \approx 0.23$ N/mm^2) and a stronger element ($f_{bt} \approx 0.50$ N/mm^2) in a model with a length of 1224 mm. The figure shows that only the initial stage of the descending branch plays a role in the present calculations. Therefore it is crucial to obtain a more detailed picture of the initial slope of the tension softening-curve. In laboratory tests only few points can be measured in this part of the stress-displacement-curve and often difficulties arise in controlling the deformation rate at this stage.

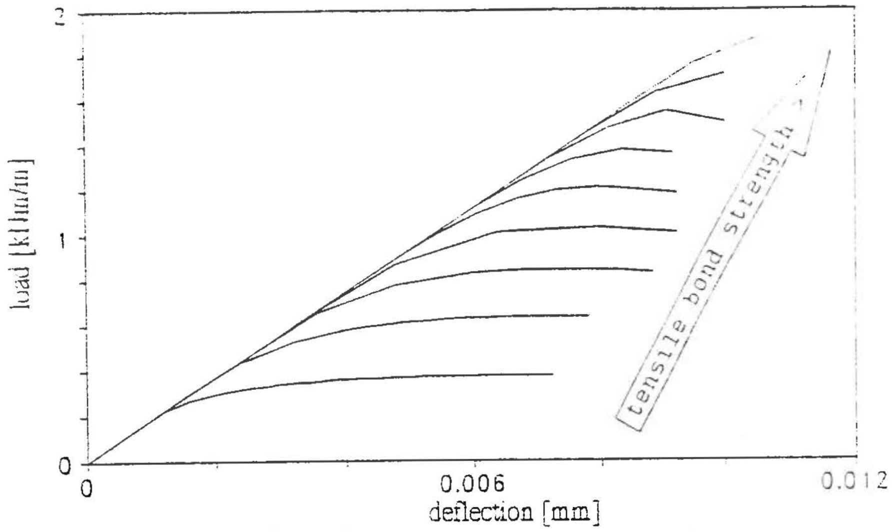


Fig. 7: Increasing ductility of cross-sections with decreasing tensile bond strength.

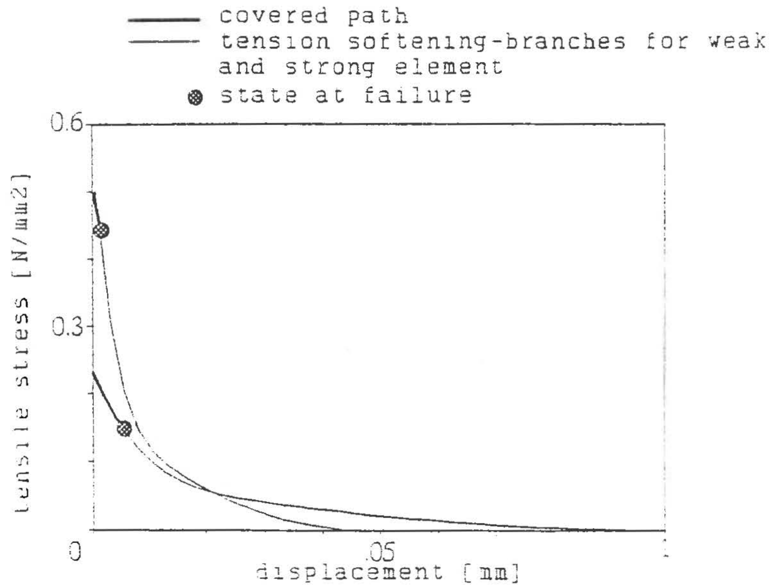
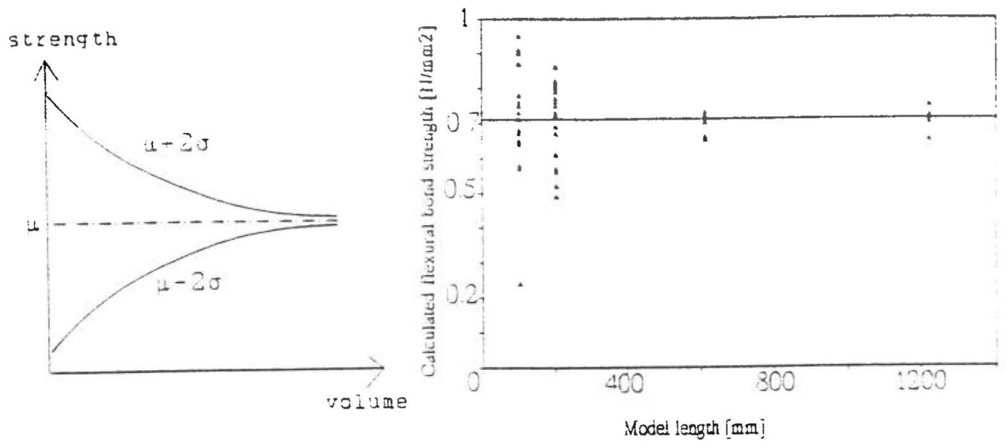


Fig. 8: Tension softening-branches for a weak and a strong element in the same model.

Interesting in the context of the present research is the concept of probabilistic systems. The numerical results show a striking resemblance with the theoretical behaviour of an ideally ductile parallel system *(fail-safe structure)* [9,10]. Such a structure shows a sharp decrease in the COV of the strength and a constant average strength value when increasing the dimensions of the structure. In fig. 9 the effect of increasing dimensions is plotted for both an ideally ductile parallel system and the numerical model.



a) parallel system b) numerical model

Fig. 9: Effect of increasing dimensions on average strength and COV for a parallel system (a) and the numerical model (b).

It can be shown that for parallel systems the COV is dependent of the factor 1/√d, in which d is the length of the structure. A curve fitting of a function *COV = constant/*√d seemed to give an acceptable approximation of the numerical results (fig. 10). It must be emphasised that only few larger models were calculated because of large computing times and the already clear reduction in COV.

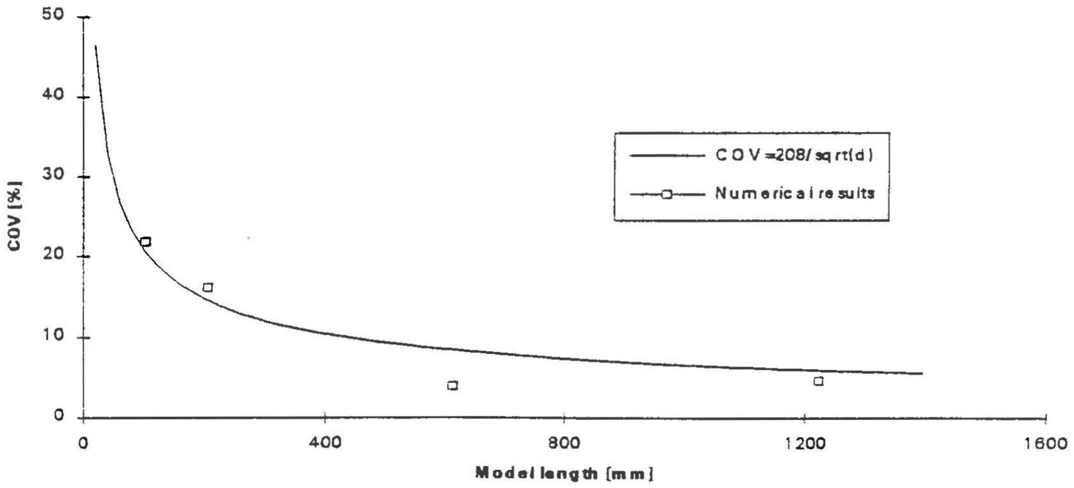


Fig. 10: Curve fitting for the relation between COV and model length.

Simultaneously with the present numerical research an experimental research (4pbt) into the flexural bond strength of masonry was carried out by Van der Pluijm [11]. Among other materials, the materials modelled in the present calculations were used. The length of the (eight) test specimens was 520 mm. Based upon the numerical results presented in this paper one would expect a COV of about 8-10% for this model length. In the tests however a COV of 17% was found.

In the following some possible causes for the discrepancy between numerical and experimental results are given:

- The applied modelling of fracture energies:

- * it might be incorrect to attribute the same amount of fracture energy to both weak and strong elements;
- * the shape of the initial stage of the descending branch might be incorrect (it could for example be steeper).
- The applied attribution of tensile bond strengths to joint elements might be incorrect. It might be possible that the number of 'zones' (i.e. half brick length areas) should be chosen less (e.g. two brick length area). It should be considered that this would influence the numerical results for a certain model length enormously.

6. CONCLUSIONS

From the numerical research presented in this paper some conclusions can be drawn that are worthwhile considering in further research:

1. The flexural bond strength (perpendicular to bed joints) is found to be highly dependent on the average tensile bond strength in the failing joint;
2. The way in which the descending branch of the tensile stress-displacement curve is modelled plays a leading part in numerical simulations concerning the flexural bond strength;
3. An apparent resemblance was found between the numerical model and a probabilistic parallel system.

The lack of consistency between the presented numerical results and related experimental results is still a subject of research. Some possible causes of this discrepancy were described in this paper.

ACKNOWLEDGEMENT

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