COMPUTATIONAL ASSESSMENT OF RENOVATION INTERVENTION IN A HISTORIC MASONRY BUILDING

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ABSTRACT

During the last three decades the renovation of existing buildings has become a rapid growing segment of the building construction market in Europe. The reasons range from the historical value of such buildings to the environmental impact of demolition. In many cases such buildings are intended for a new function. Special interventions are then required, which may effect the structural integrity of the buildings. In this paper the proposed interventions for the renovation of ``De Adelaar'', an old Dutch masonry building built in 1906, which has been listed as a monument, are analysed. The building has been severely damaged internally by the aggressive nature of the soap manufacturing process, its original function. Recently, it has been proposed for re-use as an office building. Having had no thermal insulation originally, a novel way of insulating the building is called for to avoid large differences in temperature between the external, load bearing masonry walls and the internal concrete structural frame. Large temperature differences may cause large differential deformations, which, when constrained by connecting structural elements, may cause structural damage. To minimize the temperature difference, an internal climate wall has been proposed. Yet, still significant thermal interaction is foreseen, calling for numerical analyses. A finite element model, which was recently developed for the analysis of creep, shrinkage and cracking of cementitious materials, has been employed to study the restrained thermal shrinkage of the masonry walls. The results indicate that standard insulation interventions will indeed cause severe damage, even in the event that dilatations are introduced in the walls. Also, despite the reduced thermal action in the case of an internal climate wall, some localized cracking will occur. The distribution of these cracks by carbon fiber reinforcement on the wall insides provides a simple, pragmatic solution. It is shown by finite element analysis that crack widths are reduced to within acceptable levels upon such reinforcement.

Key words: masonry, renovation, reinforcement, shrinkage, cracking, finite elements

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INTRODUCTION

The renovation of existing buildings has become a rapid growing segment of the building construction market in Europe. The reasons range from the historical value of such buildings to the environmental impact of demolition. In many cases such buildings are intended for a new function. Special interventions are then required, which may effect the structural integrity of the buildings. In this paper the proposed interventions for the renovation of ``De Adelaar'', Fig. 1, an old Dutch masonry building built in 1906, which has been listed as a monument, are analysed.

To change the function of the Adelaar from a soap factory, to an office building, insulation is required. Because of its historical value, the exterior esthetical appearance should not be altered. Therefore, insulation will be applied internally. This intervention will cause large temperature differences between the load bearing masonry walls and the reinforced concrete floors and beam-column frame. Due to rigid connections between these structural elements, damage is expected in the walls. Possible solutions are the reduction of the inter-element temperature difference by placing an internal climate façade, the reduction of restraint by replacing the concrete floors with timber, dilatations in the walls, or reinforcement of the walls to control cracking upon restrained shrinkage.

To study the effect of the interventions, numerical simulations and analyses are performed. A finite element model is employed, which was developed recently (Lourenço 1996, van Zijl 2000) for the analysis of structural masonry under mechanical and environmental (thermal/hygral) actions. With this tool the cracking in the restrained, shrinking masonry walls is predicted as a function of the inter-element temperature difference, which enables the structural impact of the insulation method to be evaluated. The reduction in the crack widths due to remedial measures such as dilatations, more flexible floors and wall reinforcement is quantified.

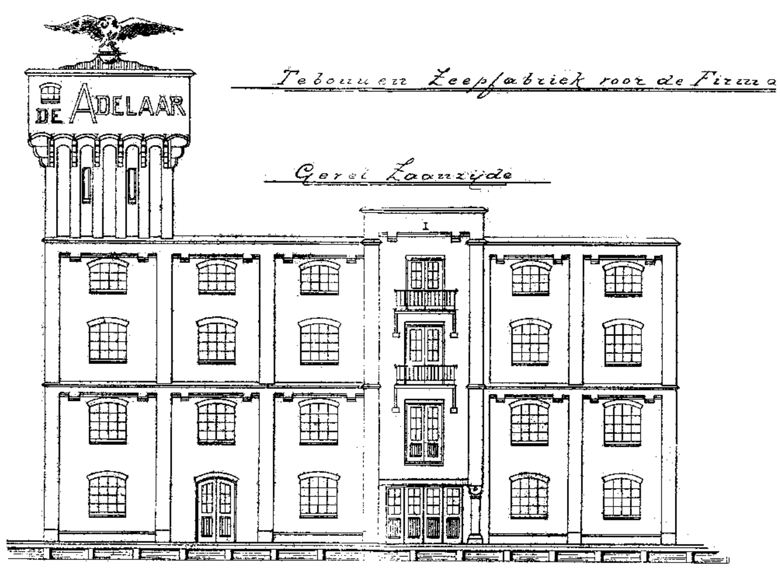

Figure 1. 'De Adelaar' soap factory (Vuyk 1906) façade facing the river Zaan.

PROBLEM DEFINITION

The building is in poor condition, with cracks in the brick walls and the concrete carbonated and aggressively attacked by the soap producing process. With contemporary knowledge the building can be repaired. However, it is imperative that the visual impact of the building is retained and that the damage does not re-occur in its new function.

<u>The structural problem</u>

The Adelaar structure comprises load bearing masonry walls combined with an inner grid of reinforced concrete columns, beams and floors, Fig. 2. By the connection of these structural elements, the movement demanded by their thermal and hygral differences is restrained, causing stresses and cracking.

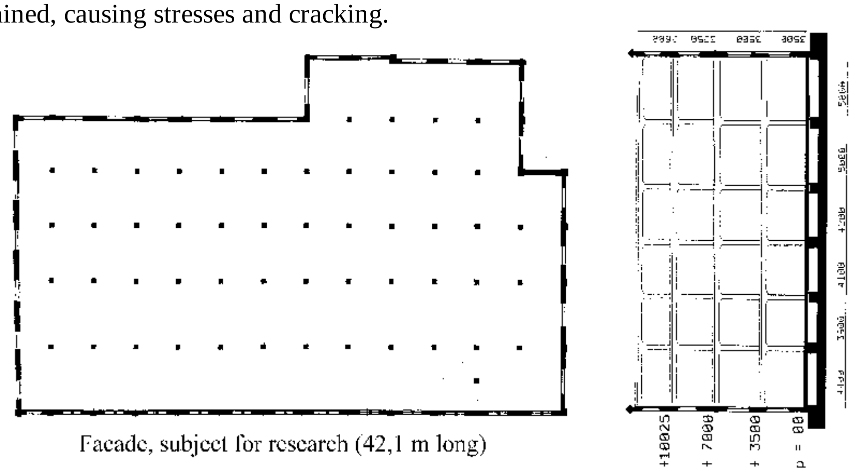

Figure 2. Floor plan and cross-section of ‘De Adelaar’.

<u>The interventions</u>

To facilitate the change of function, the building must be insulated. To retain the exterior brickwork appeal, the insulation should be placed on the inside, either directly to the inner face, or in the form of an internal climate. The source of cracking, which will be even worse after insulation has been placed, must be identified and measures taken to eliminate it, or control crack widths to remain within limits of acceptability.

A suitable insulation method, which ensures that no condensation will occur (Hogeslag and Verhoef 1989), is shown in Fig. 3a. Also shown is a simple schematisation of the extreme thermal conditions through the wall section. A conditioned internal air temperature will be approximately constant at T_i=22ºC. The external face will have a minimum temperature T_e=-10ºC and a maximum T_e=+40ºC. The schematic differences are thus ΔT=18ºC in summer and ΔT=-32ºC in winter. An internal climate-façade, Fig. 3b, is a novel way to reduce the large temperature difference. This will lead to thermal gradients in the masonry, but these are believed to have insignificant structural effect. The average temperature difference, which causes the greatest problems, will be reduced roughly by half (ΔT=+9ºC in summer, ΔT=-16ºC in winter).

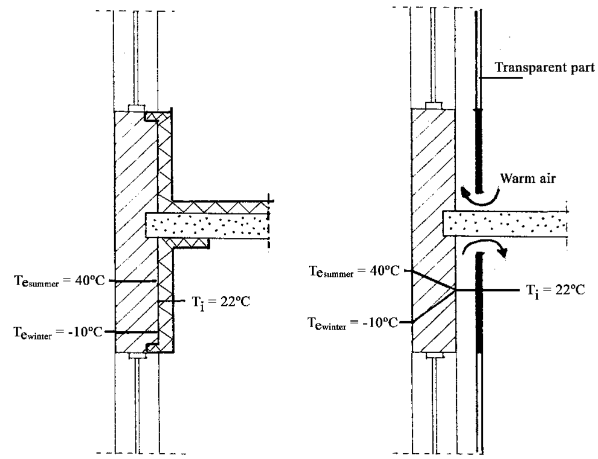

Figure 3. Schematic temperature flow with (a) insulation (b) internal climate façade.

A reduced restraint to the thermal shrinkage will reduce the level of cracking in the walls. Another historical Dutch building, 'Oranje Nassau Kaserne' which has an undilated 260m length of similar masonry type walls as the Adelaar, but timber floors, has no visible cracks.

Dilatations in the masonry walls may control the cracking. Due to their esthetical impact, a minimum number should be made. Alternatively, carbon fibre reinforced plastic (CFRP) may be glued to the wall inner faces. The total crack width in a damaged area may be spread over several cracks of smaller width. Such reinforcement has been employed successfully to strengthen masonry buildings (Schwegler 1994, 2000).

MODELLING

To study the effect of the interventions, numerical analyses are performed. The finite element (FE) model employed was developed for the analysis of structural masonry under mechanical and environmental actions (Lourenço 1996, van Zijl 2000). Orthotropic Rankine plasticity captures cracking and a (visco-elastic) Maxwell chain the relaxation. Thermal or hygral shrinkage histories can be prescribed, or analysed by the FE solution of non-linear diffusion equations governing moisture migration and heat conduction. The model has been shown to simulate concrete and masonry behaviour with reasonable accuracy by the verification and validation analyses of experiments.

It suffices to study a representative wall part. A one-storey high part of the 42.1m long rear wall is modelled, Figs. 2,4. The walls have a constant thickness of 330mm except at the piers on which the concrete beams rest, where they are 440mm thick. To limit the problem size, the wall is modelled as a two-dimensional (2D) plane, considering in-plane actions only. This approach ignores bending caused by the temperature gradients through the wall and, perhaps more importantly, the eccentric floor-wall connection. However, it is believed that the in-plane actions dominate. Symmetry is also assumed, which allows one half of the wall to be modelled. To further reduce the total size of the problem, the

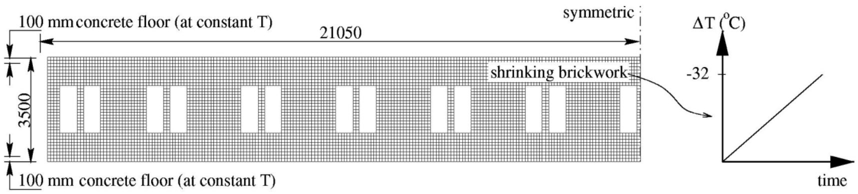

Figure 4. Schematisation of ‘De Adelaar’ wall. Dimensions in mm.

wall is considered as a homogeneous continuum. The bricks and mortar are not modelled separately, but as a homogenised composite. The orthotropic Rankine limit surface accounts for the heterogeneous nature of masonry, for instance by considering different tensile strengths parallel and perpendicular to the bed joints. The temperature variation is assumed to have the largest impact, with only negligible hygral shrinkage, because of the fired clay type masonry. As indicated in Fig. 4, a linear temperature evolution is considered. The uncertainty about the environmental processes renders a sophisticated analysis of the thermal evolution unjustified.

Due to the complexity of the structural constraints, two sets of boundary conditions are investigated, Fig. 5. In the first case (boundary 1), the left edge of the wall is assumed to be fully fixed by the lateral wall, while in the second case (boundary 2) it can translate horizontally free from the lateral wall. In both cases the bottom and upper edges of the wall are assumed to remain horizontal. Although it can be considered, no slip between the floors and the walls is allowed. This is justified by the Coulomb friction resistance, enhanced by the upper bearing loads, especially in the lower storeys of the building. A 1m wide strip of the floor is assumed to actively resist the brickwork shrinkage. Apart from the own weight of the modelled wall part and floors, the weight of one upper story is applied on the top edge. Properties typical of masonry composed of fired clay bricks and hydraulic lime mortar are employed (Leijendeckers *et al*. 1997, TGB 1990), see Table 1. Due to the uncertainty of the true values, sensitivity studies are performed (section 4.3). Furthermore, relaxation will initially not be considered. In section 4.3.3 this beneficial effect is studied.

Boundary 1

Boundary 2

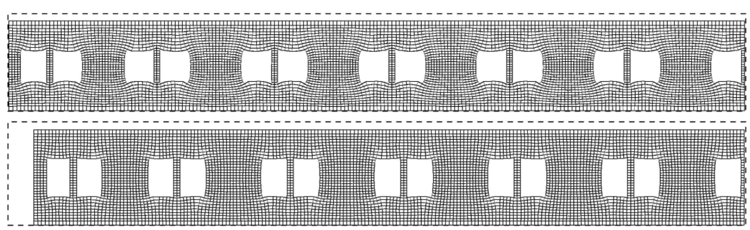
Figure 5. Schematization of wall constraint.

Table 1. Model parameters.

	E (GPa)	ϕ_c	ν	f_{tx} (MPa)	f_{ty} (MPa)	α $(^oC^{-1})$	ρ (kg/m^3)
Masonry wall:	5	2	0.2	0.4	0.2	7×10^{-6}	1900
Concrete floor:	30	0	0.2	∞	∞	12×10^{-6}	2400

E = Young's modulus
ν = Poisson's ratio
ϕ_c = creep coefficient (after 100 days)
ρ = mass density
f_{tx} = tensile strength parallel to bed joints
f_{ty} = tensile strength perpendicular to bed joints
α = thermal expansion coefficient

RESULTS: UNREINFORCED WALLS

The results reported in sections 4.1 and 4.2 are for the model parameters in Table 1, instant cooling down, which gives no time for stress relaxation and tough masonry, i.e. a cracked wall part can continue to transfer a stress equal to the material's virgin tensile strength. Subsequently, in section 4.3 the parameters are adjusted in a sensitivity study.

No dilatations

The response is summarised in Fig. 6 in terms of the maximum crack width evolution with temperature drop. The rightmost, solid lined crack width versus temperature difference curves apply, i.e. the ductile responses. The crack strains at two stages of cooling, at $\Delta T=-21^oC$ and $\Delta T=-32^oC$ are shown for boundary case 2. It is clear that this boundary case is more favourable, as cracks initiate only at about $\Delta T=-10^oC$, while for boundary 1 crack initiation already starts at -7^oC. The true response will lie somewhere between these values. At -21^oC cracks are predicted at the upper and lower corner of each window, which propagate up and downward respectively under further cooling to -32^oC. Note that the brittle cases, the dashed lines in Fig. 6 top, have not been analysed. The dashed lines merely indicate the expected sudden 'snap' to a large crack width (along the arrows) upon increased shrinkage in brittle masonry walls (van Zijl 2000). Such a snap can be analysed with special arc length methods. However, inertia plays a role, calling for a dynamic analysis. This has not been done here.

This prediction of cracking at a relatively low temperature difference between the concrete floors and the brickwork indicates that some cracks must exist in the building in its current state of no insulation. It is confirmed by the observed cracks traversing vertically from window opening to the upper story window opening in the building.

With dilatations

The effect of two dilatations in the wall as a remedy for the destructive shrinkage restraint is investigated. The wall response is shown in Fig. 7. The translational freedom relieves the stresses in the wall in close vicinity of the dilatations. However, further away cracks still appear and may even grow wider than when no dilatations have been made.

Sensitivity study

The large spread in the properties of masonry material justifies a study of the sensitivity to the most important parameters. In the subsequent analyses the solid wall, i.e. without dilatation, is analysed with boundary 2 acting. In each case the parameters of Table 1 are employed, while only the specific parameter under investigation is varied.

Masonry tensile strength: The influence of the tensile strength parallel to the bed joints (f_{tx}) is investigated. In the absence of strength test data, a value of 0.4MPa was taken from the literature. It is well known that a large coefficient of variation is found in masonry strength tests. Therefore, the analyses have been repeated for f_{tx}=0.2 and 0.6MPa, Fig. 8a. A significant influence is seen in the figure, with the crack initiation temperature drop range $-4^oC<\Delta T<-14^oC$ for this range in masonry strength.

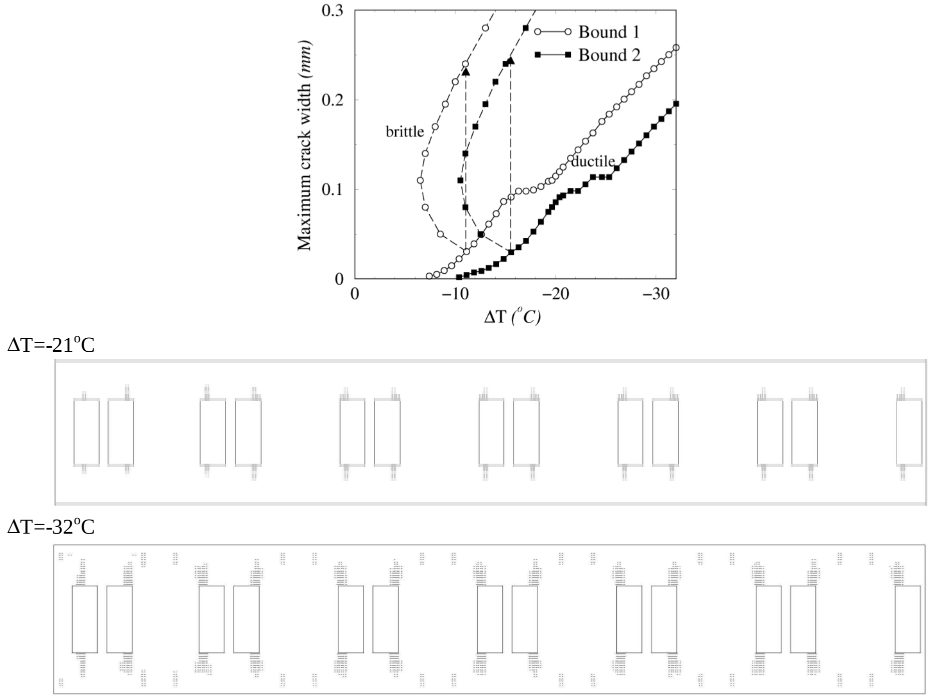

Figure 6. Cracking due to shrinkage restraint. Crack strains shown for bound 2.

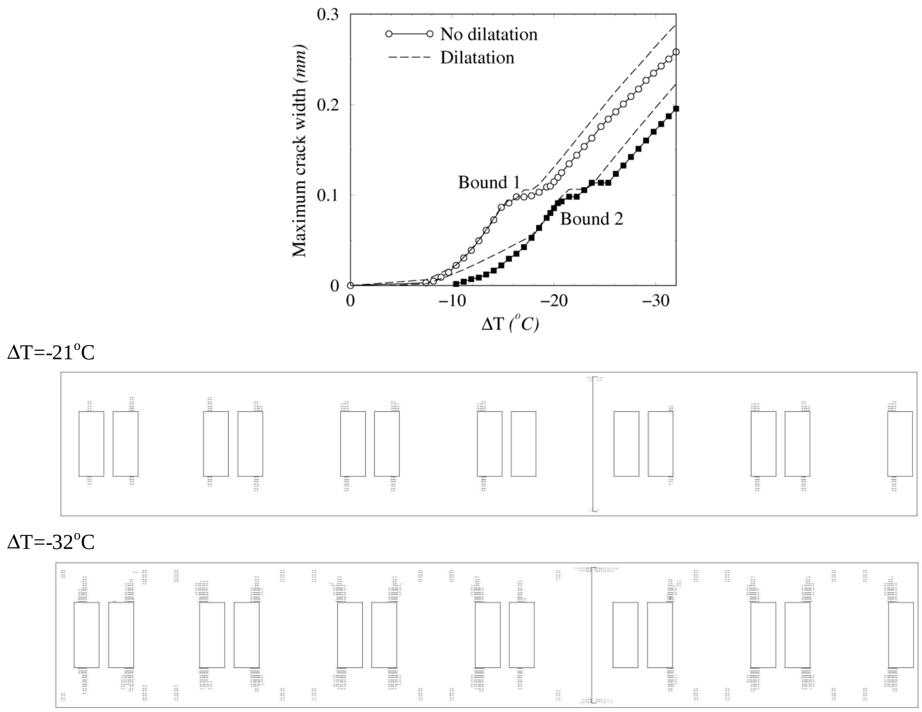

Figure 7. Cracking due to shrinkage restraint of wall with dilatation.

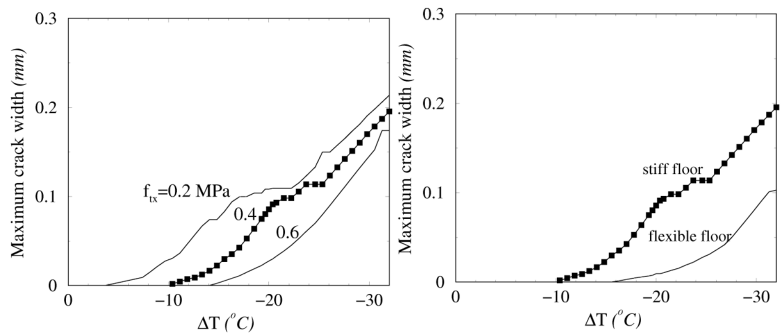

Figure 8. Sensitivity to (a) masonry strength and (b) floor stiffness.

Floor stiffness: The concrete Young's modulus is known with a high degree of certainty (Hogeslag and Verhoef 1989). The motivation here is to investigate whether a more flexible floor type, for instance timber, will prevent cracking. In Fig. 8b the wall response for a floor of stiffness E=10GPa is compared with the case of concrete floors E=30GPa. The reduction in the shrinkage restraint stiffness has a favourable effect.

Time dependence/relaxation: The inherent viscous nature of cementitious materials like concrete and masonry relaxes the stresses and postpones crack initiation to higher levels of shrinkage, or even completely prevents cracking (van Zijl 2000b). This is investigated for the Adelaar by varying the duration of the thermal half cycle from instantly to 100 days, Fig. 9. The worst case is found when the temperature drop occurs instantly, while slow cooling allows the wall stresses to relax and crack initiation to be postponed to a larger temperature difference.

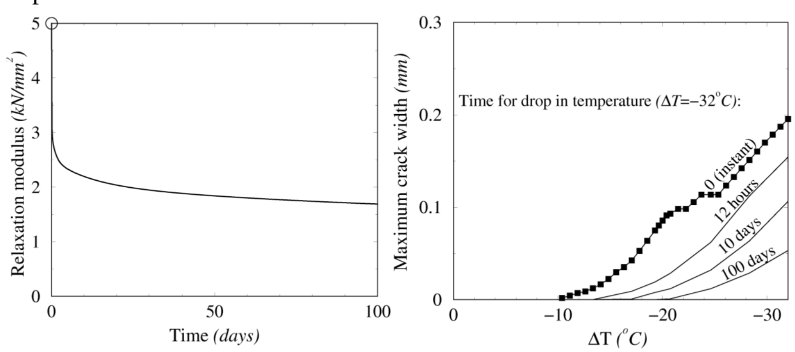

Figure 9. (a) The relaxation modulus.(b) Better shrinkage resistance for delayed cooling.

DISCUSSION

The shown results and their parameter-sensitivity allow some conclusions to be drawn about the proposed interventions. It is very probable that cracks of unacceptable width will occur in the Adelaar if the walls cool down by 32^{o}C relative to the concrete floors. This will be the case even in the scenario of no lateral restraint by the perpendicular connecting wall (bound 2, Figs. 6,7), a high tensile strength (f_{tx}=0.6Mpa, Fig. 8a) and if the temperature difference evolves over 12 hours (Fig. 9b). The Adelaar masonry can be classified as brittle (van Zijl 2000), which implies that the snap-through shown in Fig. 6

will occur. The introduction of two dilation joints in the brickwork is no remedy. It merely relieves the brickwork locally, while the cracks further away remain. If a lower temperature difference between the brickwork and the restraining floors can be realised by an internal climate wall, no significant cracking will occur for boundary condition 2, f_{tx}=0.4MPa and a 12 hour temperature cycle half-period (Fig. 9b). However, it is likely that weak spots exist (f_{tx}<0.4MPa). Cracks may already initiate at these weak spots and, upon fast cooling (no relaxation), will snap to large widths.

The lower level of cracking in the case of a flexible (timber) floor, Fig. 8b, which will be even lower if the temperature drops in 12 hours instead of instantly, goes a long way towards explaining the non-occurrence of significant cracking in the 'Oranje Nassau Kazerne', another Dutch building. However, a timber floor is undesirable for The Adelaar. A pragmatic solution may be sought in the FRCP-sheet reinforcement of the walls to prevent crack snap-through to undesirable widths.

WALL REINFORCEMENT

FRCP-sheet reinforcement glued onto masonry walls has been shown to strengthen masonry walls (Schwegler 1994, 2000). With its high stiffness E=155GPa and strength f_t=2400Mpa it may avoid the serviceability limit-state of The Adelaar being breached.

Crack distribution action illustrated

To illustrate the effectiveness of CFRP-sheet reinforcement to reduce crack widths in masonry, a small masonry wall part is analysed in plane stress, Fig. 10. The specimen comprised 2 layers of 4 bricks (210x52x100) in running/half bond. The central head joint and brick have a 5% lower strength than the other to simulate imperfection and seed a single, wide crack in the masonry. A discrete cracking approach is followed (van Zijl 2000), with interface elements capturing cracking at masonry joints, as well as through the centre of each brick. The two ends of the specimen are restrained horizontally. The upper and lower edges are constrained to allow vertical translation, but with equal amount, i.e. the edges remained horizontal. In this way the confinement caused by surrounding masonry (not modelled) is simulated. The masonry is assumed to shrink at a constant rate. The response is shown in Fig. 10. In the unreinforced specimen, cracks initiate in all the head joints, after which the central crack snaps through the brick to a large width. Next, 0.8mm thick FRCP-sheet reinforcement is modelled over the whole surface of the specimen. Perfect bond is assumed. Despite the central masonry imperfection, cracks now open at all head joints and gradually traverse vertically through each connecting brick, Fig. 10. A much smaller maximum crack width has been achieved by spreading the cracks over the specimen length. Due to its high stiffness, the CFRP-sheet effectively reduces crack widths in restrained shrinking masonry by transferring stress from damaged areas to undamaged areas. In this manner more cracks, but of smaller, acceptable width arise.

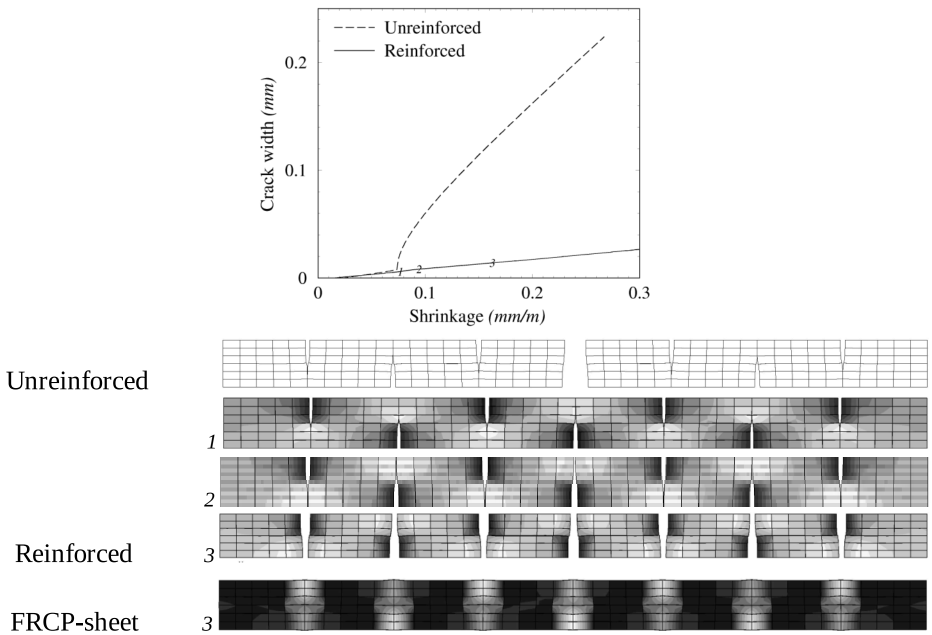

Figure 10. Responses of unreinf. and CFRP-sheet reinf., restrained shrinking masonry specimens. Contours: Masonry: max. principal stress: black +0.2Mpa white +1.0Mpa
FRCP : horizontal stress comp.: black –20Mpa white +70Mpa.

<u>Reinforcement of 'De Adelaar' walls</u>

Encouraged by the improved restrained shrinkage behaviour of CFRP-sheet reinforced masonry, the effect of such reinforcement on The Adelaar is investigated. The FRCP-sheets are modelled by overlapping horizontal rows of existing quadrilateral elements, with which the walls have been modelled, with additional quadrilateral elements. Strips of 0.8mm thick and 106mm wide are modelled continuously over the whole wall length. To avoid the aesthetic impact of external CFRP-sheets on the walls, only the inside faces should be reinforced. This will increase the bending effect caused by thermal gradients. However, this is assumed to be negligible and not considered here. The glue is not modelled, which implies that perfect bond is assumed. From private discussions with the author Schwegler (2000), a bond length of up to 1m is required to develop the CFRP strength. By applying the strips continuously over the whole length, this requirement is met, except at the wall ends, where the distance to the first window opening is only 600 mm. Depending on the stress level in the reinforcement there, additional strips may be applied locally to reduce the bond length requirement.

Two cases are considered. In the first case a single strip is applied directly below and above the window openings respectively. In the second case, two more strips are applied, each half-way between the first strip and the concrete floor. The responses are shown in Fig. 11. Instead of a single, wide crack at the outer corner of each window when unreinforced, several vertical cracks occur, spread over the total window width. The maximum crack width is reduced to approximately 0.1mm for both cases of reinforcement. Note that for the reinforced walls, the true brittle masonry fracture energy values have been employed. Despite this fact, no snap-through of cracks occur in the reinforced walls. It is recalled that ductile behaviour had to be modelled to avoid snap-through in the unreinforced wall, indicated by the dashed line in Figs. 6,11.

The non-shrinking FRCP-sheets are forced into compression by the shrinking wall between the cracks. At the cracks they are stretched to bridge the cracks, causing tension. A maximum tensile stress of 65Mpa occurs, well below their strength. This does not imply over-reinforcement, because the stiffness is required to keep the crack widths small. Also, the low stress is favourable for the bond length requirement.

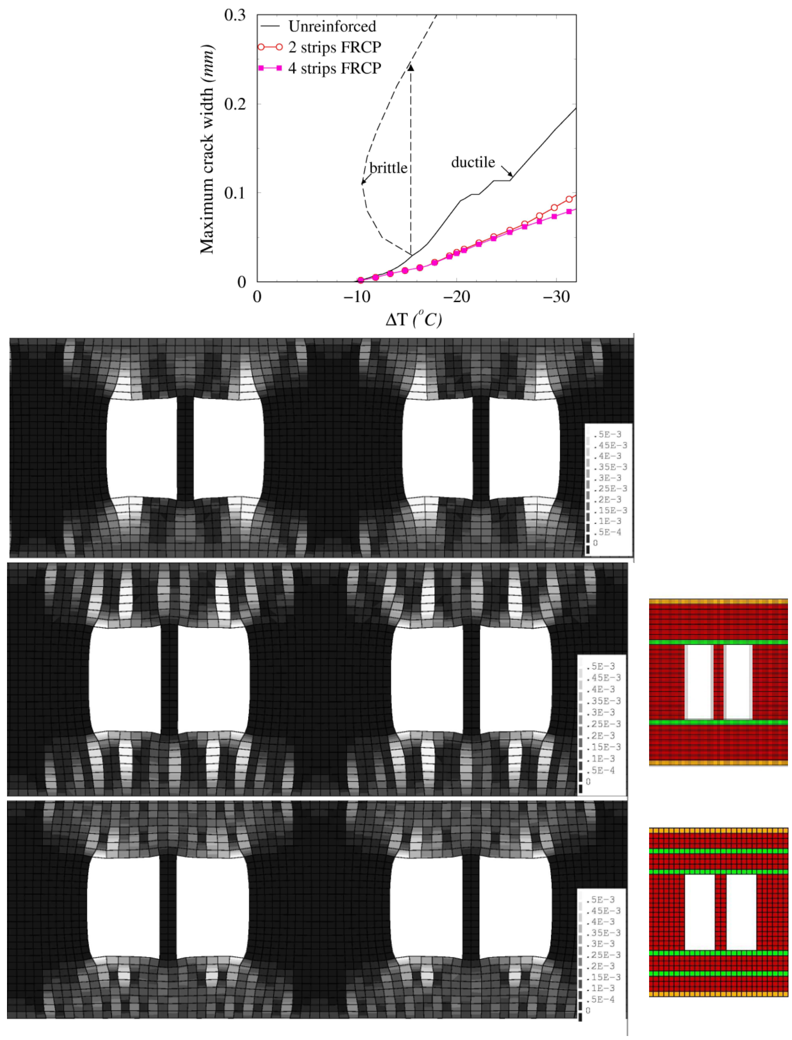

Figure 11: 'De Adelaar' unreinforced and CFRP-sheet reinforced wall responses to restrained shrinkage. Top: Max. crack width vs. temperature. Bottom: Crack strain contours for unreinforced wall, wall reinforced with 2 strips and 4 strips CFRP-sheet.

CONCLUSIONS

The structural impact of renovation interventions in an old Dutch building has been quantified by finite element analysis. It has been predicted that the introduction of insulation on the inner wall of 'De Adelaar' will cause unacceptable cracking in the walls. Dilations in the walls resolve the cracking only locally. To be effective, a dilatation must be made at each window, which is unacceptable for this historical building. A reduction in the temperature difference between the restraining concrete floors and the brickwork by an internal climate façade does not sufficiently reduce the danger of large cracks snapping through at the window openings.

The control of crack widths to acceptable levels by FRCP-sheet reinforcement has been shown numerically. Two continuous sheets directly above and below the window openings suffice to prevent crack snap-through. Instead of a single, wide crack as in the case of no reinforcement, several vertical cracks of small width arise. Furthermore, it has been shown that the application of two more strips produces a slight reduction in the maximum crack width and prevents crack snap-through in the wall parts between the first strips and the concrete floors at high temperature differences. Action is currently undertaken for the practical application of FRCP-sheet reinforcement in 'De Adelaar'.

ACKNOWLEDGEMENTS

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