THREE REMARKABLE CASES OF STRUCTURAL DAMAGE DUE TO IMPOSED DEFORMATION

VERFORMUNGSBEDINGTE SCHÄDEN AN MASSIV-KONSTRUKTIONEN – DREI FÄLLE AUS DER PRAXIS

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SUMMARY

The report deals with three cases of structural damage which are due to excessive deformation. The first concerns the transition wall of two town houses, the second a wall in the furnace of the anode bakery in an aluminum factory, and the third the fully prestressed strand in a trussed roof girder. The first and second cases are due to alternating temperature cycles, the third is due to creep and shrinkage of concrete. It is being discussed what the causes for the damage were and what measures have been taken.

ZUSAMMENFASSUNG

Drei Schadensfälle an Beton und Mauerwerk werden behandelt, die auf übermäßige Verformungen zurückgehen. Der erste Fall betrifft die Trennwand zwischen zwei Reihenhäusern, der zweite Fall handelt von einem Anodenbackofen in einem Aluminiumwerk, beim dritten Fall entstanden Trennrisse in einer voll vorgepannten Betonkonstruktion. Bei den ersten beiden waren zyklische Erwärmung mit anschließender Abkühlung die Ursache, beim dritten waren Schwinden und Kriechen in der statischen Berechnung nicht berücksichtigt. Es werden Ursache, Verlauf und Folgen des Schadens diskutiert, als auch die getroffenen Maßnahmen.

1. INTRODUCTION

Temperature cycles mean deformation cycles which do not necessarily lead to a damage. If a structural member is completely confined it means that a temperature change will cause stresses according to $\sigma = E\,\varepsilon = E\,\alpha_T\,\Delta T$, with E the elastic modulus, α_T coefficient of thermal expansion, T temperature. For longer periods, E should be replaced by $E/(1 + \rho\phi)$ with ϕ creep coefficient and ρ the relaxation coefficient. If the structural member is free to expand no stresses will be built up. A similar situation will develop due to shrinkage of concrete. Then, $\alpha_T\,\Delta T$ has to be replaced by ε_s which is the shrinkage strain.

What is said above holds only as long as the material stays in the elastic stage. As soon as the material cracks or crushes the rigidity drops and new considerations have to be made. This is also the case for cross-sections composed of several materials with different coefficients of thermal expansion and mechanical properties. If the particles or layers are bonded together thermal or shrinkage stresses will develop irrespective of boundary conditions (internal restraint).

The paper reports on the situation of developing damage, the amount of deformation, the stresses involved, and the damage. Further, strategies of actions taken will be commented.

2. PARTITION WALL OF TOWN HOUSES

2.1 Situation

Typical town houses in the Netherlands have two or three stories the upmost of which has an uncovered space (terrace) which is separated from the neighbor's house by a partition wall. Houses built in the first half of 20th century have that wall made of brick, houses of later time are mostly made of concrete. The present report deals with a brick wall. The ground plan is straight forward with two houses side by side separated by a brick wall.

The partition wall is a straight extension of the indoor wall, is built in stretcher or quarter bond and is built in a single unit breadth. Since the wall is outdoors it is exposed to rays of sunshine and low temperature during the night and winter time. When the wall is heated up it will expand according to the thermal coefficient. The wall which is discussed here is exposed in south-west direction which means that it caches the full sunbeam. The lower part of the wall is protected against the sun. Thermal expansion is highest at the top of the wall. Fig. 1 shows the permanent expansion as it appeared after about 70 years in service.

Fig. 1: Thermal permanent expansion of the partition wall

Cooling down means shortening of the wall. If the wall is homogeneous and uncracked it goes back into the original shape. What happens when the layers have different temperature and the hottest layer has slid on the base or on the layer underneath then friction will hamper the back movement and tensile forces develop. Since masonry has very little or almost no tensile strength cracks develop and a permanent elongation will occur. When the cracks are filled up with debris of the joints this permanent elongation is growing with each cycle. After many years the present wall has been grown half the breadth of the brick.

The wall has grown in the upper part more than in the lower. This can be due to the vertical load which is increasing towards the base. Higher normal stress means also larger friction which restricts the sliding movement of the brick layer during warming up, and the formation of cracks during the curing down phase also is improbable. Thus, warming up and down follows the temperature cycle but not synchronously. On the upper part of the wall, sliding of a brick layer is possible and the formation of cracks as well. Looking to Fig. 1 the largest deformation did not happen right on the top but some layers lower. Maybe the soldier bricks on top have reduced cracking or, when a number of parallel cracks separate an unreinforced slab or wall a package can develop by chance which obviously is the case. Maybe the situation was aggravated by frost action and ice forming in the joints.

2.2 No urgent measures

This example of imposed deformation does not immediately lead to structural problems but rather is a question of esthetics. No measures have been taken so far. When the whole town house is going to be renovated in the future the damaged wall will be replaced [1].

3. ANODE BAKING FURNACE[1]

3.1 Furnace building

The production of aluminum is a multistep process. One step is the electrolytic reduction of aluminum oxide. This is performed in a cryolite bath with a high amperage direct current which necessitates large anodes [2]. The anodes must be "baked" in a baking furnace. The green anodes consist of tar pitch and petroleum coke which is compacted to prisms of considerable size of about 1.0 x 0.5 x 0.5 m^3. Many of them are assembled in the furnace and heated up to about 1,050°C. Although the walls of the furnace have fire proof insulation the concrete is warmed up to about 200°C at the inner face. The furnace which will be dealt with, is an open reinforced concrete box of 6.5 m width and 150 m length with a depth of 5 m.

Cross walls divide up the length of the box into compartments of about 10 m. The furnace is located on a site with soft ground and rests on piles. Fig. 2 schematically shows the cross section of the building. Two furnaces are arranged in longitudinal direction. The left box is empty while the right box is equipped with the combustion chambers and the anode receiving chambers in between. The thermal insulation is also indicated. For handling the anodes in fresh and baked state a crane runs along the building. The clear span of the crane is 26 m. The rails rest on the outer columns of the roof structure. Under the handling platform there are installations for the factory operation.

[1] This case has been mentioned in [4]

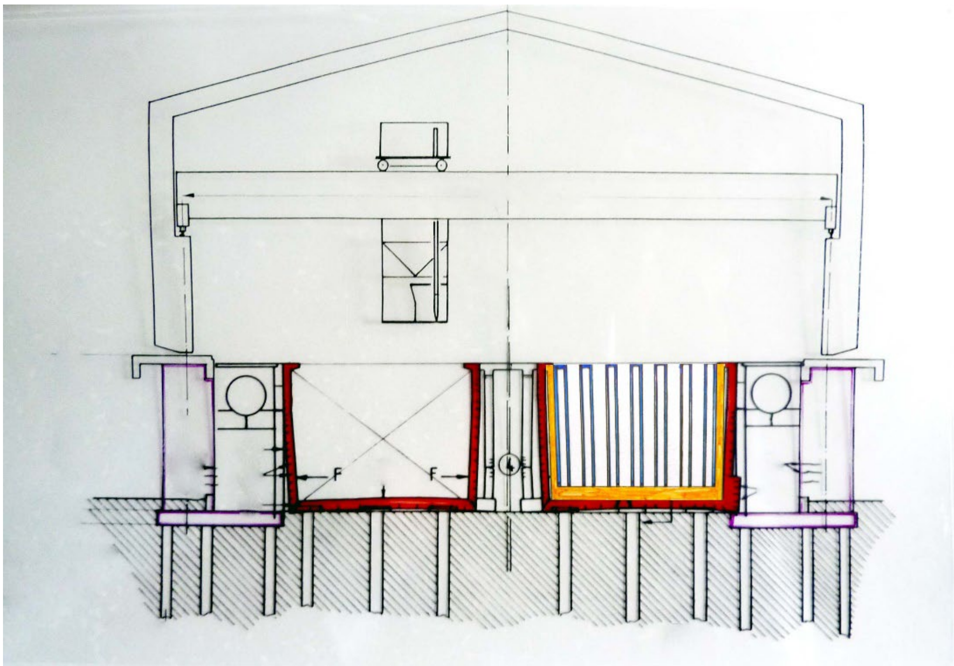

Fig. 2: Cross-section of furnace building (from [3])

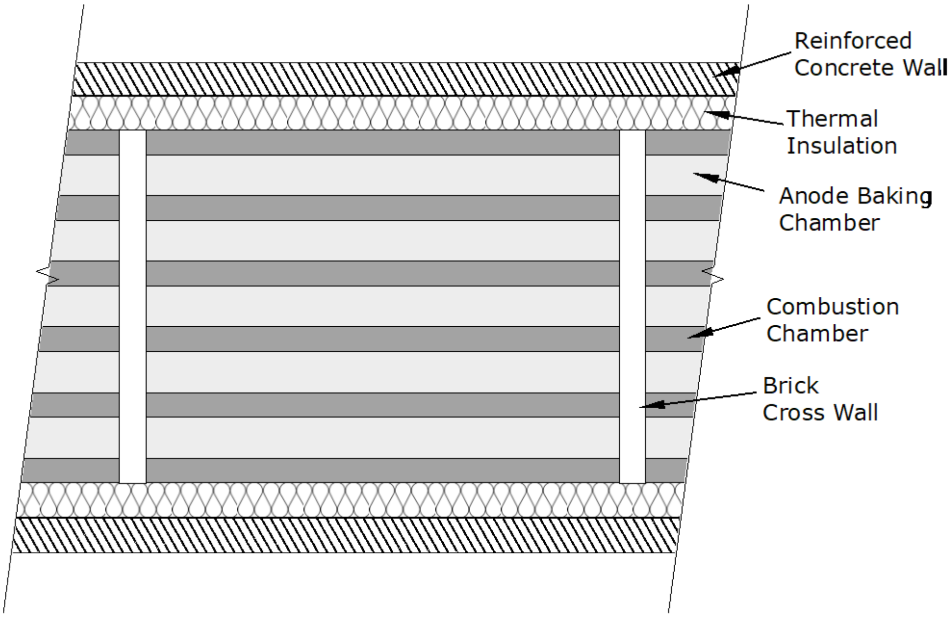

Fig. 3: Horizontal section of the anode baking furnace, schematic, not on scale with reinforced concrete wall, fire-resistant thermal insulation, anode baking chamber, combustion chamber and brick cross-wall (Drawing, courtesy Tilman Reinhardt)

Fig. 3 shows schematically a horizontal section of a furnace which is the core part of the anode production facility. The concrete box contains the combustion chambers and the anode baking chambers (baking shafts) which are arranged side by side and take turns. They run in longitudinal direction.

3.2 The baking process

The furnace building covers two furnaces, a crane track and working platforms parallel to the furnaces. What happened? During the baking process which takes about 3 days (warming up, holding the temperature, cooling down) the concrete box is warmed up to a mean temperature of about 100°C and dilates. Normal to the outer wall, the partition cross-walls made of fireproof bricks are heated up to about 1,000°C and dilate much more. They are rather stiff and push on the thermal insulation of the concrete walls and compress it. During cooling down to bearable working temperature, the thermal expansion goes back, but not completely. Cracks in the masonry are formed and partly filled up with pitch and coke. This happens every cycle with the consequence that the cross-walls grow more and more, compress the insulation and push on the concrete wall of the furnace. Shear forces develop in the lower part and bending forces in the whole side wall.

3.3 Deformed structure

Fig. 4 shows the situation on a picture taken in longitudinal direction between the two furnace boxes. The bottom of the furnace has become larger and has pushed on the reinforced columns which support the working platform. The columns were only slightly reinforced and became severely cracked. The platforms got normal forces and transmitted them to the outer columns which carry the bearings of the columns of the roof and the crane track. One was afraid that the crane could be derailed and collapsed. A look to Fig. 5 unveils the width of the main crack and the minimal reinforcement.

Fig. 6 shows the outer side wall of the furnace which is bent and cracked in a regular pattern.

Fig. 4: Deformed concrete box and cracked columns (from [3])

Fig. 5: Column with large crack, showing the small reinforcement (from [3])

Fig. 6: Outer side wall of the furnace (from [3])

The wall is leaning against the columns of the working platform. The lower part of the wall has been repaired by adding a reinforced concrete supplement in order to increase the shear resistance of the wall. On the right side of the picture one can see a dilatation joint of the furnace.

3.4 Measures taken

What measures have been taken? First, to check the stability of the structure, it has been converted to a computer model taking account of the deformation and the cracks. Second, the structure has been analyzed again. (It was not easy to convince the engineers of the owner that the problem was a deformation problem and not a force problem.) From the calculation, it came out that the structure was still stable, but it was advised to shore the outer walls of the furnace and to monitor the state regularly.

This provisional action was only justified for a certain period of time. A new furnace building was already in planning and has been constructed within two years. It was however important that the production of anodes was not interrupted.

On the other hand, the structure has shown considerable redundancy in the state of deformation. And, a deformation problem has to be analyzed very carefully before expensive and maybe useless measures are taken.

4. FULLY PRESTRESSED GIRDER WITH TRANSVERSE CRACKS

4.1 The structure

The roof of a service hall was composed of sheds resting on a trussed girder the lower chord of which was a fully prestressed concrete beam with rectangular cross-section. Fully prestressed means that no tensile stresses develop in the service state. Tensile bending stresses in the outmost fiber are counteracted by prestressing and thus no cracks will develop.

However, a case of damage has been reported. The roof structure showed considerable transverse cracking in the lower tensile chord of the truss. How could it be possible? There are several possibilities: the prestress may be lower and/or the load was higher than specified. Both arguments were checked but the result was negative.

Another possibility was that some assumptions in the static analysis were wrong. A check of the calculations showed indeed that creep and shrinkage were not considered. The structure was older than the date of introducing creep and shrinkage into the standard. After checking the calculation with the phenomenon creep and shrinkage it turned out that this could have been the reason for transverse cracking. The background deliberations can be found in [5]. (A simplified approach: If the tensile force in the lower chord is equal to the prestressing force, the concrete is stress-free. If, additionally, creep has reduced the initial prestressing force then the concrete can get tensile stresses and cracking may occur.)

Fig. 7 depicts the statical system of the roof structure. Fig. 8 shows the sheds resting on the trussed girder on which measurements were executed.

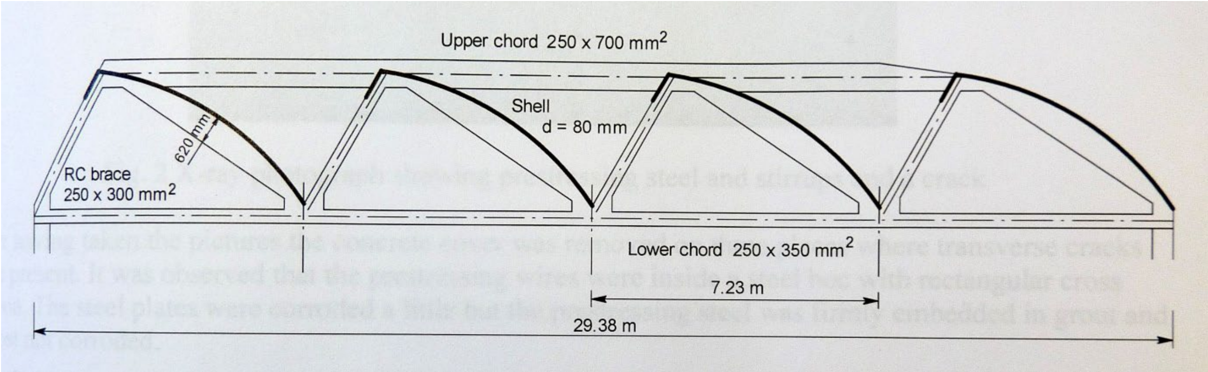

Fig. 7: Roof structure (from [5])

Fig. 8: The sheds resting on the trussed girder

4.2 Signs of damage and measurements

The lower chord is an almost pure tensile member on which transverse cracks have been found. They have been discovered when large rust stains could be seen, Fig. 9.

Fig. 9: Corrosion products on lower side of tension chord

The stains follow cracks of destroyed concrete cover which are caused by corrosion of stirrups. The rust was a token that the girder should be observed more carefully since the hall served a business with large damp production.

For inspection, destructive methods were ruled out. The methods should find out the location of reinforcement and the type of steel. As nondestructive method the radioscopy with gamma rays was chosen [6]. Depending on the density of the material in which the gamma rays penetrate the exposed film shows a bright or dark picture. Reinforced concrete contains steel with high density, dark, and concrete with lower density, grey. Air shows up bright.

The following Fig. 10 gives an impression. On the figure one can see at the very bottom dark lines which represent steel. Further vertical dark lines represent stirrups.

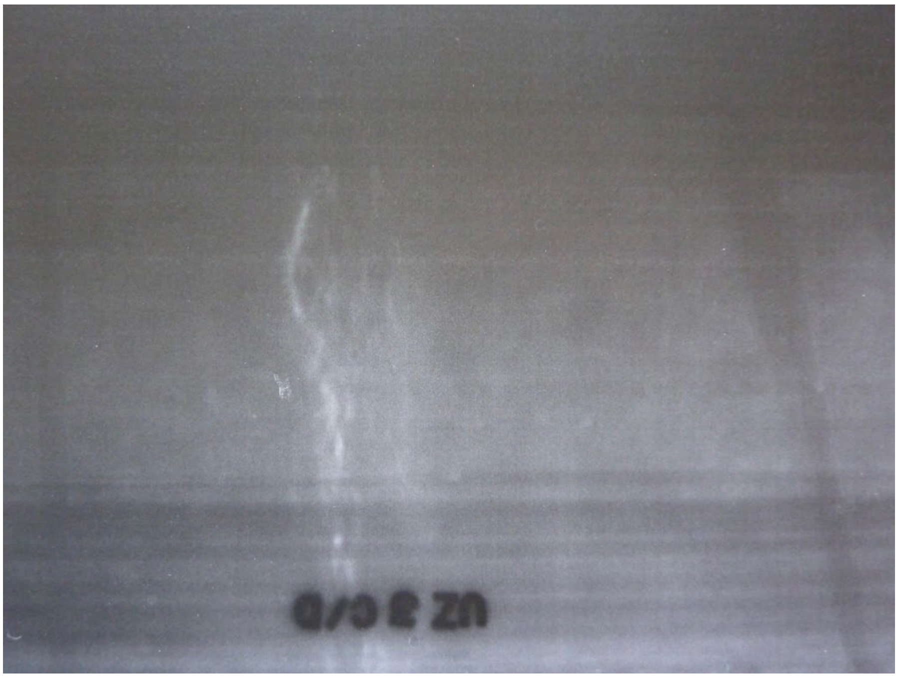

Fig. 10: Dark lines on bottom of the chord indicating prestressing and reinforcing steel, vertical dark line caused by stirrup, bright lines due to cracks in concrete

According to the original static analysis which was still available thin prestressing wires were used what was confirmed. Fig. 10 gives additional 1nformation by the vertical bright lines which represent cracking. Of course, several pictures were taken which is necessary for a thorough inspection. However, they did not give any other information.

The measures taken were regular inspection and continual observation.

5. GENERAL DISCUSSION

The three cases described above dealt with deformation and subsequent damage. Forces develop only if the deformation is restrained either by boundary conditions or internal restraint. The difference between a force induced problem and a deformation induced problem is that the loads in the first case are known, while in the second case they develop due to the rigidity of the restraining element. A typical situation is a structural member in between two walls which is growing or shrinking. If the walls are stiff and strong the force in the member gets large however, if the walls crack the rigidity drops and the force is small or vanishes even.

Internal restraint may be due to different materials in a cross section which are glued together forming a multilayer structure, an example is plywood or more general cross-laminated timber. Shrinkage along the fibers is very small but normal to the fibers is large, the elastic modulus is high in the first case and is low in the second. So, the cross lamination prevents (or reduces) shrinkage of a board made of plywood.

A force induced problem has immediate influence on the stability of a structure while a deformation induced problem may be tolerated as long as the elements involved have sufficient deformation capacity maybe due to plasticity or crack formation.

6. CONCLUSION

Three examples of damage due to imposed deformation are presented which led to the following conclusion:

a) The deformation of brick walls due to severe ambient temperature cycles is a frequent phenomenon mostly without structural consequence. Repair is difficult and replacement is often necessary.

b) An anode baking furnace is exposed to very harsh temperature changes. In this case, it was heavily cracked and extremely deformed due to temperature cycles and deposit of pitch and coke in the masonry joints of the transverse cross walls.

c) Although the concrete structure showed large deformation and cracking a thorough analysis of the current state confirmed sufficient stability.

d) The measures taken were only possible on private ground where the owner takes the full responsibility for the safety of people which are allowed to enter the place.

e) Further, the replacement of the furnace building was necessary in the near future.

f) Transverse cracking of fully prestressed concrete elements can occur where creep and shrinkage are not considered in the static analysis. There was no immediate danger but in order to maintain this stable situation the prestressing wires have to be protected against corrosion.

g) Students are mainly educated in force induced problems. They should learn more about deformation induced problems.

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