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Title:

DEF-pathology in concrete supporting a lock-gate: use of numerical modelling to re-assess structural behaviour

Abstract:

Delayed ettringite formation (DEF) is a concrete pathology which may occur in structural parts submitted to high temperature during their casting, such as some massive elements cast in-situ. DEF consequences can lead to structural disorders (expansions, cracking, deterioration of mechanical properties), which modify and jeopardize structures serviceability and sometimes, safety.

This communication deals with a concrete lock for which a large prestressed beam supporting the lower gate is affected by DEF for several years.

First, the structure and its pathology are described. The global strategy of the study, mixing together documents analysis, laboratory tests on concrete samples and use of finite-element models is then presented. These numerical models have multiple purposes: assessing the early-age thermal history of the beam in order to confirm the origin of DEF; assessing the structural behaviour and its modification due to DEF, based on chemo-mechanical coupling models; mechanical interaction between the beam and the other parts of the lock. This modelling is performed to assess structural state at present time, as well as to predict its evolution in the future.

Finally, conclusions drawn from the study are used to help structure owner in their planning of his maintenance policy.

1 - The structure and its pathology

Ettringite is one of the products formed during cement hydration. In sound concrete, ettringite crystallizes at early-age, while concrete is still plastic, without any consequences. In some cases, if temperature raises during cement hydration, ettringite cannot be formed immediately. Hence, its formation occurs later, in

hardened concrete and crystallization pressure induces material damage and global swelling. This pathology is then called Delayed Ettringite Formation (DEF) (Divet, 2001). One of the common causes responsible for excessive temperature at early-age is the heat produced by cement hydration, especially in massive structural elements.

The Fontinette lock (built in 1965, this lock with a 144,60 m x 12 m chamber is on the Neufossé channel, part of the Dunkerque-Escault-Lille link) is equipped with two miter gates (upper and middle) and a lower guillotine gate (see Ill. 2). Due to the exceptional 13 m rise, the lower gate is topped by a “mask” girder. The mask girder consists in two parts (see Ill. 1) between which the gate slides: the upstream part protect the gate from boat shocks and the downstream one support water pressure when the chamber is full and bears a technical gallery. For resisting these high loads, the downstream girder is prestressed in two directions (22 cables “STUP” consisting of 12 8-mm tendons in the vertical direction, 122 cables of the same type in the transversal one).

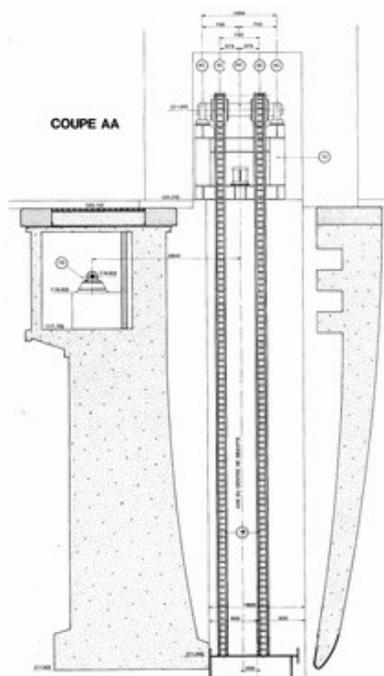


Illustration 1: Cross-section of the mask-girders and the lower gate (opened), downstream on the left.



Illustration 2: Downstream part of the lock with the lower gate and its mask-girders.

In 1997, evidences of internal swelling reactions have been discovered in the downstream girder. Alkali-silica reaction (ASR) has been observed on samples, and DEF is also suspected (investigations still on-going). Possible long-term consequences of these pathologies could be a decreased of concrete resistance due to internal cracking, compression stresses in the girder due to prescribed swelling and excessive traction in the tendons. This is why a numerical model has been developed to: first, confirm the possibility of DEF in conjunction with the truthful ASR; second, to estimate the mechanical consequences of the pathology onto the lock structural safety.

2 - Global strategy of the study

The numerical modeling of DEF-effect in the downstream girder is a three-step strategy, connected to the global management of the lock which includes documentation research, monitoring, sampling of concrete and laboratory analysis. We decided to focus on the sole DEF because there exists no numerical model taking into account simultaneous occurrence of both ASR and DEF and because DEF is well-known to be more dangerous (quicker and with larger swelling) than ASR.

The first step consists in re-assessing the early-age thermal history occurring during the casting of the girder, based on documentation from the enterprise in charge of construction and from meteorological statistics. This thermal history is then transformed into a swelling potential, which requires fitting some unknown parameters relative to the development of DEF in this particular concrete. Since, at this step, these parameters are unknown, typical values from the literatures are used. Once the model for concrete swelling is done, it is coupled in a mechanical model (forming a *chemo-mechanical model*) and allows us to assess the mechanical consequences of DEF in the girder. By comparing these consequences to values from the monitoring and to experiment results obtained on concrete samples from the structures, the chemo-

mechanical, the chemo-mechanical model is then fitted. This last step being still on-going, we will only describe the two first steps in the following sections.

3 - Numerical model for DEF-affected concrete

The first step is to re-assess the early-age thermal history. This step is performed by solving the heat transfer equation in each lift of the girder (6 lifts have been successively cast) and introducing cement hydration heat as a source (Tailhan *et al.* 2010). At each point of the girder, the thermal history is transformed into swelling potential using model developed by (Baghdadi *et al.* 2008).

The swelling potential is then converted into an incremental prescribed strain representing swelling of the concrete and its effects are computed taking into account boundary conditions, loads, as well as the presence of reinforcements and prestressing cables. The influence of stress-state is also considered, both as inducing anisotropy in the swelling and as a classical creep mechanism. Evolution of DEF is also represented by a degradation of mechanical properties through a damage equation. This chemo-mechanical procedure is described in (Seignol *et al.* 2012).

4 - Application to the beam supporting the lower gate

For numerical modeling, the downstream girder of the lower gate is represented by about 97,000 finite elements and divided into six parts, for each successive lift. The early-age thermal history is then computed and, as shown on Ill. 3 for the 3rd lift, we confirm that temperature exceeded 65 °C in the central part of the structure (this value is usually considered as the threshold temperature above which DEF can occur).

In the second step, we introduce classical values for the swelling parameters, and the structural effects of DEF are observed on the same mesh (into which bar elements have been introduced to reproduce groups of prestressing cables). The evolution of the girder versus time can be observed, for instance 50 years after construction, as seen on Illustration 4: the central and upper part of the girder is subjected to high displacements (about 10 mm) whereas the bottom and side of the element are blocked by the surrounding parts of the lock, leading to internal compressive stresses. This model will soon be fitted to be more consistent with observed measurements as well with recent observations on concrete samples.

5 - Conclusion

In this (on-going) work, we try to put the stress on two important points concerning the management of waterway infrastructures affected by delayed-ettringite formation:

- the complex and serious consequences of DEF onto mechanical behaviour of concrete elements, hence onto structural safety of critical infrastructures;
- the possibility offered by numerical modelling to test assumptions and to estimate consequences (now and in the future) of DEF, and its conjunction with informations obtained from documentation research, in-situ monitoring and laboratory analysis.

6 - References

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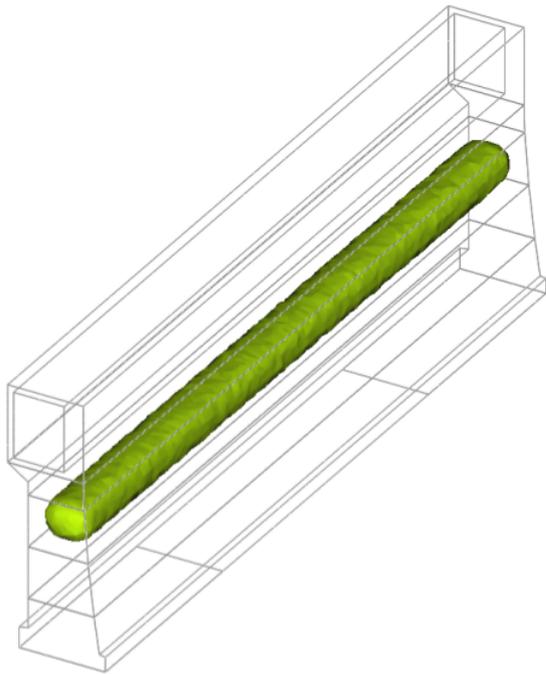


Illustration 3: Zone where temperature at early-age reaches 65°C in lift #3 (numerical simulation).

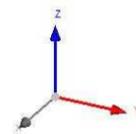
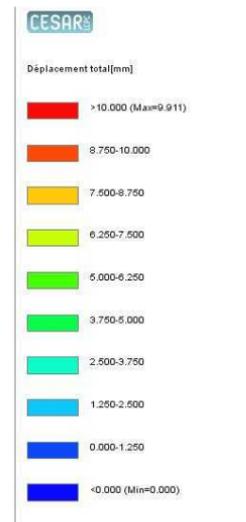
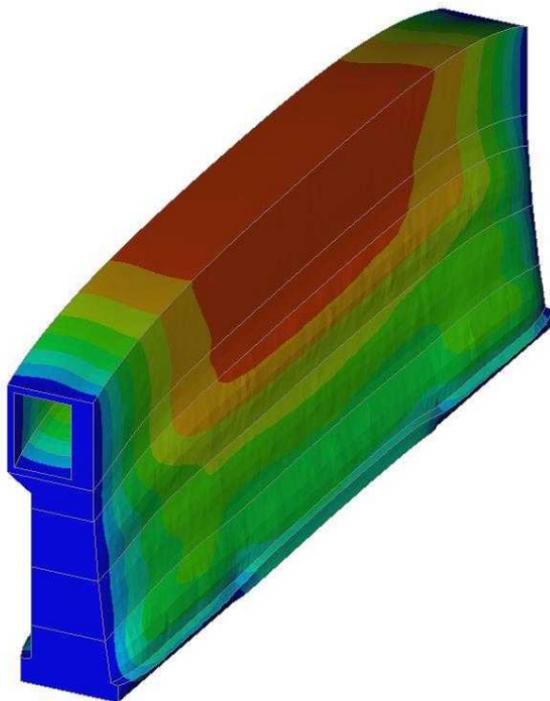


Illustration 4: Deformation of the downstream girder after 50 years of DEF, and map of global displacement (numerical simulation).