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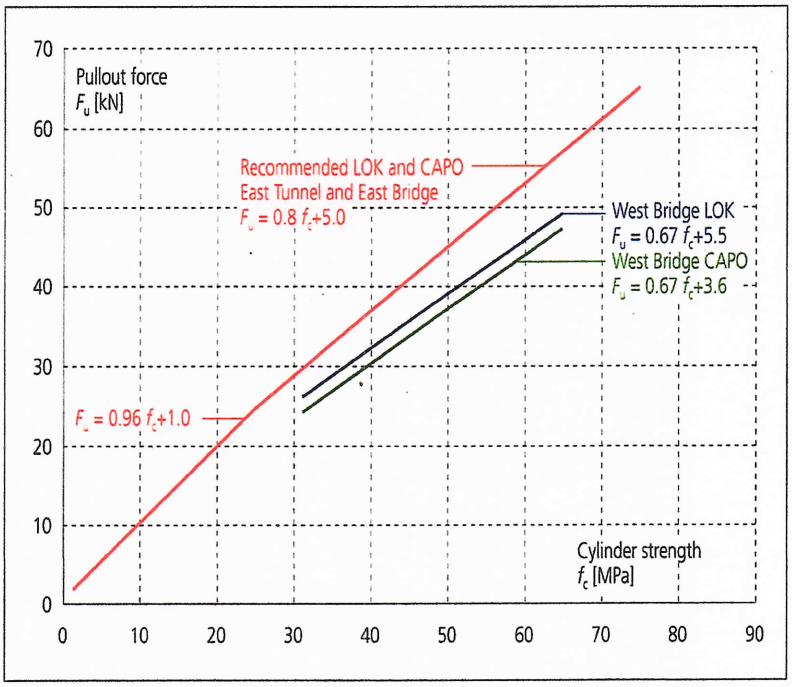
Case 5.4 Scrutinizing correlations used for in-situ production control at the Great Belt Link´s West Bridge, Denmark

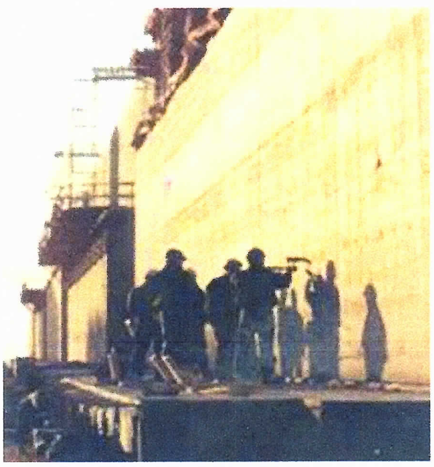
For production control at the Great Belt Link project, constructed between 1990 and 1994, the correlations used relating pullout force by LOK-test and CAPO-test to cylinder strength are shown below, for the East Tunnel, the East Bridge and for the West bridge of the project, ref 1, page 170

▸ *Fig. 5.3-3 Recommended correlation (red) between LOK-test and CAPO-test pull-out forces and 150mm diameter x 300mm long standard test cylinder compressive strength. This correlation was used for the East Tunnel and East Bridge whereas separate correlation relationships (blue and green) were established for the West Bridge*



Note: The red "recommended" correlation reported in 1992, ref.3, p.8, has later been simplified into one general correlation **$f_{cyl} = 0.69\ F_u^{1,12}$**, relating cylinder strength f_{cyl} in MPa to pullout force, by LOK-test of CAPO-test, in kN pullout force, used from 1992 and onwards, refs. 5, 6 and 7

LOK-test´s and CAPO-test´s general correlations, one to cylinder strength, and one to cube strength are documented in details in refs. 5. 6 and 7. **These general correlations are the essential foundation of the Danish pullout systems.**
The blue and the green correaltions in the figure above from GBL´s West Bridge are different from the general correlation to cylinder strength, producing about 23% higher cylinder strength for a given pullout force. This has never been seen before.
The purpose of this case is to scrutinize this deviation, clarify the motives for the change, and come to a conclusion wheather or not the green and the blue correlations are valid.



CAPO-testing of the caissons slipformed vertical faces of the GBL´s West Bridge caissons.

Background:

The CAPO-test pullout forces were found to be to low for production control acceptance using the red "recommended" correlation in the figure above, no matter how much curing was applied to the slipformd surface.

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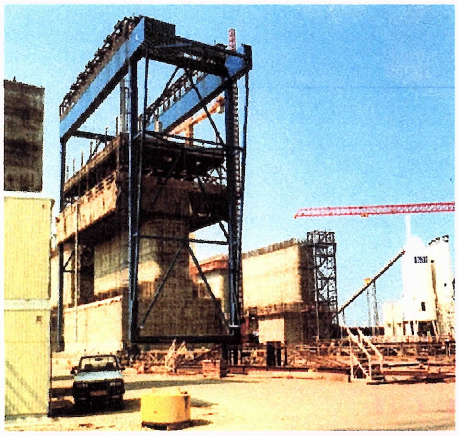

Slipforming of a Caisson for the West Bridge

About the slipformed cover layer:

Ref. 1, p. 211: *"Petrographic results showed cracks, porosities and separation in the cement paste of the cover concrete. In particular many surface parallel defect could be observed"*

Ref. 2, p. 129: *"Investigations showed that the defect could not be avoided, They were caused by the filling of the small slip, that occurred between the concrete and the steel form each time the form was lifted", "Also. An investigation was made on other slipformed structures in Denmark. All these structures showed similar defects"*

Ref. 2, p. 130: *"At the time, where the problems were discovered, it was no longer possible to change the slipforming concept without causing serious delays to the whole project, and it was decided to proceed with the slipforming concept"*

Ref.1 p. 212: *"In conclusion, the defects appeared to be an inherent part of the slipforming concept, and could not be avoided unless the production concept was changed, which was not practically and ecomically possible".*

As the slipform concept on the caissons could not be changed, and the cracking of the caissons cover layer could not be avoided, the main conclusion was:

Ref. 1, p. 215: *"To remedy the effects observed in the petrographic testing is was decided to install cathodic protection systems on all the West Bridge´s caissons".*

This gives certainly a perspective quite different than the one attempted on the Great Belt Link – to produce good quality coverlayers with the needed service life for chloride intrusion, without resorting to cathodic protection.

In other words, the cover layers certainly had lower CAPO-test pullout strength than the "interior", with reduced resistance to chlorides.

Now, back to the the subject of this case, the correlations:

The red "recommended" correlation shown on the previous page was questioned by the GBL for the West Bridge caisons, and it was decided, cf. ref 1, p. 1, to:

"Carry out a correlation test for the actual West Bridge concrete. For this purpose several test blocks were prepared , each 400 mm x 200 mm x 200 mm, and fitted with four LOK-test bolts (on the vertical face). After four days of maturity six blocks were LOK-and CAPO-tested, and at the same time 18 lab cylinders were strength-tested. The tests were repeated after 7, 28 and 56 day´s maturity and the average pull-out forces plotted against the cylinder strength. It was found that the West Bridge correlations for LOK-test and CAPO-test were not identical with the recommended correlation".

Type B mix was used.

The cylinders cast and compacted on vibration table, demoulded after one day and cured in water.

Ref. 1 is not mentioning how the concrete blocks were produced, but it is known that plywood forms were used, and the concrete in the forms cast and produced outside the laboratory.

What is certain, is that the required ACI correlation procedure was not followed, as specified in ref. 3, page 85-100, by which standard cylinder strength is related to pullout strength on 200 mm x 200 mm x 200 mm cubes, cast, compacted and cured in water in the laboratory, exactly as the cylinders, and tested at the same maturity.

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In addition, an important unknown factor, the curing of the blocks, is not mentioned anywhere in ref. 1.

In this manner the West Bridge correlations shown on the first page was produced, generating approx. 22 % higher MPa strength for a given CAPO-test pullout force.

Strength Requirements, ref.1, p.170:

Potential Strength — In-Situ Strength

Table 5 3-1 Requirements to 28 days characteristic strength

	Mix type	Cylinder tests	LOK/CAPO tests
East Tunnel	A1	50MPa	40MPa
	B	45MPa	36MPa
East Bridge &	A	45MPa	36MPa
West Bridge	B	45MPa	36MPa

The compressive strength of the concrete obtained in a real structure is always less than the strength of the same concrete measured on standard specimens in the laboratory. This is because of the workmanship during the constructions, e.g. the effects of transportation, pumping, consolidation and curing

The reduced value of strength, the design strength, is obtained by applying safety factors to the characteristic strength obtained by standard specimens in lab conditions.

In the Great Belt project, the ratio between the minimum accepted characteristic strengths of standard cylinders and in-situ tests was 1.25.

With the "new" West Bridge correlation found for CAPO-test, the slip-formed caissons cover layer quality was accepted using CAPO-test with the lower characteric value obtained in May 1992, calculated to be f_{ck} = 36.7 MPa, just above the required limit of 36.0 MPa , cf ref.1 p. 172

REMARKS

The reason for the shift in the West Bridge correlation curves compared to the recommended correlation is, beside not adhering to the specified correlation procedure, believed to be caused by lack of proper curing of the concrete blocks for the pullouts.

Attempting to clarify the influence of this one factor, the curing, the Author´s company did its own investigation.

In this investigation reported in ref. 4 "Case 5.1; Curing of the cover layer evaluated by Pullout and Bulk Resistivity and the implication on service life", air-cured specimens showed a 23% lower pullout strength compared to water cured, on the same concrete quality as the Great Belt Link´s.

On this backround the Author believe the explanation for the West Bridge´s different correlation is mainly lack of proper curing of the blocks for the pullouts, while the cylinders were made and cured perfectly in water in the laboratory.

Obviously, by coincidence, the approx.. 20% reduction in pullout strength of the cover layer (or 20% higher MPa´s) is eliminated using the West Bridge´s special performed correlation, ending up in acceptance of the caissons.

Difference in pullout correlations for the West Bridge:

Referring to the figure on the first page the correlations were:

LOK-test: $F_u = 0.67\ f_c + 5.5$ (blue)

CAPO-test: $F_u = 0.67\ f_c + 3.6$ (green)

Why the difference of approx. 2 kN between the LOK-test pullout forces and the CAPO-test´s, LOK-test being the highest?.

Answer: Planning of the surface was not done before testing with the CAPO-test on the blocks. It is imperative to diamond-plan the surface as instructed, to get the correct compressive failure, otherwise a lower pullout force will be produced compared to LOK-test, in this case about 2 kN.

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CONCLUSIONS

1. The use of slipform on the West Bridge´s caissons producted cracking in the cover layer, reducing the CAPO pullout force,

2. For acceptance of the caissons, a special correlation was produced between standard cylinders in the laboratory, and pullouts on 400 mm x 200 mm x 200 mm blocks, cured outside the laboratory. Curing was not reported.

3. The special West Bridge correlations did not simulate the cracking in the caissons cover layers, and its effect on strength. The concrete blocks manufactured in the plywood forms had no such cracking. **Only this fact makes it meaningless to use the correlations for production control acceptance of the caissons.**

4. The correct ACI procedure for correlation was not adhered to, comparing strength of 150 mm x 300 mm standard cylinders in the laboratory to pullout on 200 x 200 mm x 200 mm cubes cast, compacted and cured in water, exactly as the cylinders, tested in parallel at the same maturity.

5. The GBL correlations generated produce approximate 20% higher MPa strength compared to the recommended correlation accepted on the East Tunnel and East Bridge of the GBL project.

6. Curing in air produce approx. 23% lower pullout forces compared to curing in water.

Main conclusion:

7. **The West Bridge correlations are not valid, and should be discharged.**

Outside the scope of this case, which is to scrutinize the West Bridge correlations, it is interesting to notice:

With the new West Bridge correlations stated, the slipformed caissons were accepted.

The caissons were, due to the un-avoidable cracking and porosities in the cover layer from the slipformig finally decided to have cathodic protection installed, on all the caissons on the West Bridge of the Great Belt Link project, making CAPO-testing of the cover layer somewhat redundant.

And, cf ref.1, p. 269, 270: in GBL´s "Concrete Technology", Section "**Final Remarks and Concluions**":

"New test methods during production were put into practice, including examination of the microstructure, and pull-out testing of the important protective concrete cover so as to evaluate the real quality of the hardened concrete in the structure, and not just the potential quality basd on laboratory evaluation.

The use of pull-out testing (LOK-test and CAPO-test) is a primary recommendation for production testing*, provided that problems related to training test operators, placing test bolts, and statistical evaluation of results are solved."*

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REFERENCES:

Ref 1: Great Belt Publictions, "Concrete Technology", edited by Niels J Gimsing, A/S Storebæltsforbindelsen, Copenhagen, 1999

Ref 2: Great Belt Publications, "West Bridge", edited by Aksel G. Frandsen and Niels Gimsing, A/S Storebæltforbindelsen, Copenhagen,1998

Ref.3: Petersen, C.G. & Poulsen, E.: "Pullout testing by LOK-Test and CAPO-Test with particular reference to the in-place concrete of the Great Belt Link", Dansk Betoninstitut A/S, Birkerød, Denmark, 1991

Ref.4: NDTitans: "Case 5.1 Curing of the cover layer evaluated by Pullout and Bulk Resistivity and the implication on service life", Copenhagen, Denmark, 2022

Ref.5: NDTitans: "Case 3.1 Correlation between Pullout Force and Compresive Strength", Copenhagen, Denmark, 2022

Ref.6: Moczko.A, Carino, N. J. and Petersen, C.G.: "CAPO-TEST to Estimate Concrete Strength in Bridges" ACI Materials Journal, Nov. Dec. 2016, Technical Paper, title no. 113-M76

Ref.7: Petersen, C.G.: "Practical cases in the application of the pullout method (LOK-test and CAPO-test) for in-place compressive strength", Concrete Solutions Conf., Leeds, UK, July 2022