

Minimum Reinforcement to Crack Width Control in CMC-Facings of Large RCC Gravity Dams on base of Deformation Compatibility

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Summary

To provide serviceability and tightness of large gravity dams, which are erected by roller-compacted concrete (RCC), a reinforced conventional concrete facing (CMC) can be placed simultaneously with the RCC.

With regard to interaction between CMC-facing and RCC-dam body at hardening of CMC as well as in case of overall performance of the RCC-CMC-compound system in period of usage, crack width control in the CMC has to be guaranteed by minimum reinforcement, [1].

In continuation to former studies, this contribution concentrates on determination of required minimum reinforcement in the CMC on base of deformation compatibility within the member. In contrast to the conventional method on base of cracking force [2], this allows consideration of restraint mechanically correct.

The benefit of this deeper analysis is a reduction of the required minimum reinforcement amounts, which allows material savings and provides time efficiency.

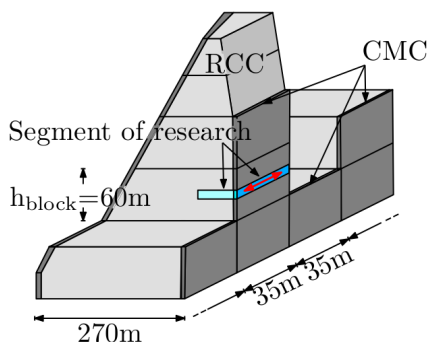


Figure 1: CMC-facing for tightness of RCC-dam; location of research segment under consideration of construction state.

Introduction

To guarantee serviceability of large gravity dams, which are erected by roller-compacted concrete (RCC), seepage and associated uplift at the upstream face must be avoided. In special cases, this requires the prevention of crack formation

in the RCC periphery, caused by thermal restraint due to hydration heat and climatic conditions at seasonal changing of ambient temperature.

With [1] the risk of crack formation in the periphery of large RCC gravity dams as well as the positive influence of a CMC facing was already presented for the conditions of the Diamer Basha Dam in Pakistan according to the planning status of 2009. The result of the whole investigation was a recommendation of thickness, construction method as well as quantification and arrangement of required minimum reinforcement amount for the CMC facing, [2].

Today current research allows the determination of the required minimum reinforcement amount on base of the compliance of deformation compatibility within the member. Beginning with a general introduction to this approach, this contribution exemplifies its application on base of the already presented CMC-facing solution for the Diamer Basha Dam.

In the course of this quantification of additional input parameters is done by using the finite element method.

Finally with this method the character of restraint is not only phenomenological (cracking force), but also mechanically correctly considered. The benefit of the deeper analysis is a reduction of the required minimum reinforcement amounts, which allows material savings and provides time efficiency.

Required Minimum Reinforcement under consideration of Deformation Compatibility

The deformation compatibility within the concrete member describes the equilibrium between deformation impact and deformation response of the system. In general this can be formulated by:

$$\alpha_T \cdot \Delta T + \varepsilon_{cs} = \varepsilon_{free} - \frac{\sigma_c}{E_c} - \varepsilon_{cc} \quad (1)$$

with: $\alpha_T \cdot \Delta T$ = temperature strain

ε_{cs} = shrinkage

ε_{free} = volume change and crack opening

σ_c = restraint stresses

E_c = modulus of elasticity at point of viewing

ε_{cc} = creep

The deformation impacts are defined by the strain due to temperature change and shrinkage and the deformation response consists of the real deformations like concrete strain and crack opening, restraint stresses depending on the modulus of elasticity at the time of viewing and the creep of concrete.

In case of the RCC-CMC-compound system this context was already investigated in [1]. Figure 2 shows the detected authoritative restraint stresses for the suggested solution of a 1.5 m thick CMC facing.

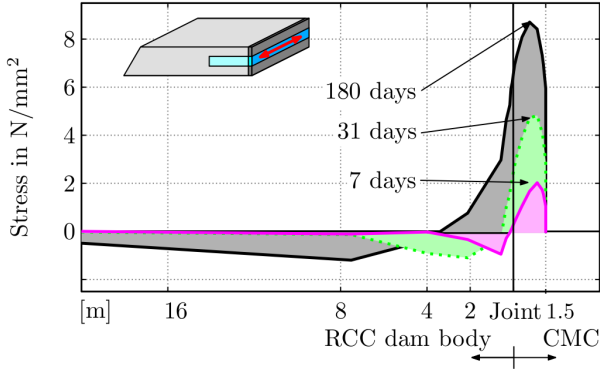


Figure 2: Restraint stress distribution in the periphery of the RCC CMC compound system with 1.5 m thick CMC facing due to hydration heat and seasonal temperature changing.

If restraint stresses reach tensile strength, cracking is likely and the deformation compatibility has to be formulated under consideration of the crack opening. This crack opening depends on height of deformation impact, distribution of restraint stresses in the cross section and crack spacing. For the investigated system, cracking occurs approximately 7 days after concrete placing and the stress distribution has the form of a triangle with the critical stress at the outer surface. At this point it is very important, if the crack spacing is set by geometric conditions or due to interaction between concrete and reinforcement. In first case, which is authoritative for the viewed CMC-RCC-compound system, the crack spacing has to be determined under consideration of interaction between CMC and RCC at over-all-performance of the compound system.

The restrained deformation is comparable with the crack opening at the surface without any reinforcement. It amounts:

$$w_{\text{rest}} = \frac{\sigma_c}{E_c} \cdot l_{\text{cr}} \quad (2)$$

- with:
- w_{rest} = crack opening without reinforcement
 - σ_c = authoritative restraint stresses
 - E_c = authoritative modulus of elasticity
 - l_{cr} = geometric set crack spacing

If the expected crack opening without any reinforcement exceeds the tolerable crack width criteria, secondary cracks are necessary. According to [3] their required number can be calculated by:

$$n = 1.1 \cdot \left(\frac{w_{\text{rest}}}{w_{\text{tol}}} - 1 \right) \quad (3)$$

- with:
- n = number of required secondary cracks
 - w_{rest} = crack opening without reinforcement
 - w_{tol} = crack width criteria

And the required minimum reinforcement to generate the described crack pattern can be quantified by:

$$a_{s,\text{req}} = \sqrt{\frac{d_s \cdot (h-d)^2 \cdot b^2 \cdot f_{\text{ct,eff}}}{w_{\text{tol}} \cdot E_s} \cdot (0.69 + 0.34 \cdot n)} \quad (4)$$

- with:
- d_s = diameter of reinforcement bar
 - h = thickness of regarded member
 - d = static height of cross section
 - b = width of regarded area
 - $f_{\text{ct,eff}}$ = authoritative tensile strength
 - E_s = modulus of elasticity of reinforcement

This formula considers, that the generation of secondary cracks leads into an increase of the steel stress in the primary cracks and an accompanying additional opening of them. Further details of this can be taken out of [3] and [4].

Determination of geometric set crack spacing

As the definition of the geometric set crack spacing is not trivial at all, a customized calculation model on base of FEM was developed. Based on a simple two layer model with shell elements, which displays the horizontal allocated segment of research under using of symmetry, the cracking process was investigated.

For this the calculation model was upgraded with failure elements within the CMC-layer, which are oriented straightly across the depth at every 20 cm. Those failure elements were cut-off, if tensile strength is reached in the element middle. For realistic results, this switching is controlled stepwise. This means, after the simulation of the initial load case with the authoritative stress distribution, only the most critical stressed failure element is detected and cut-off. Subsequent to this, the equilibrium is searched again. Afterwards the resulting state is scanned for more or new critical stressed failure elements, whereby now the next most critical stressed failure element is cut-off. And this progress is repeated until

every failure element is under the critical stress state. Figure 3 shows this calculation model.

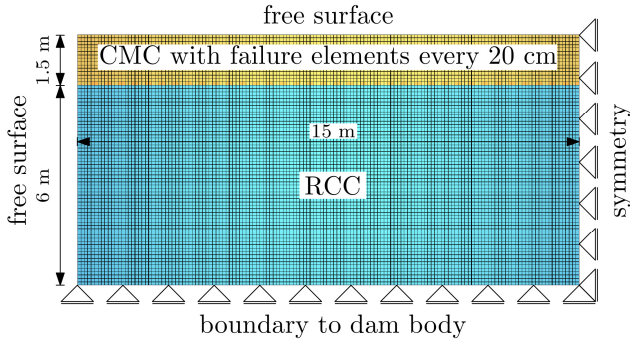


Figure 3: Calculation model for determination of geometric set spacing of primary cracks in the CMC-facing.

As this approach is only used for determination of the geometric set spacing of the primary cracks, any interaction with reinforcement and the softening effect can be neglected. But at first, the stress distribution of Figure 2 was generated by equivalent temperature loads. Figure 4 shows this initial stress distribution.

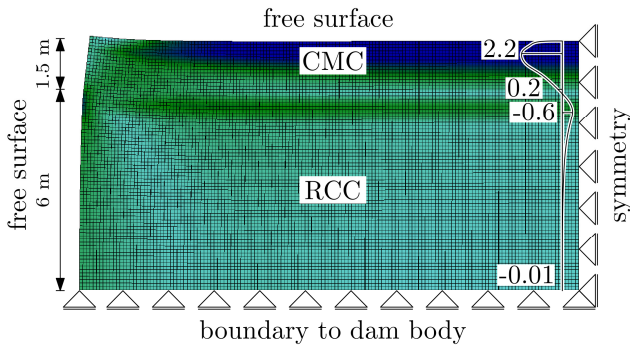


Figure 4: Implanted stresses in the RCC-CMC-system for investigation of geometric set crack spacing in CMC-facing.

In this calculation model the stiffness of RCC and CMC was defined on the safe side with their characteristic values. And the tensile strength of CMC for controlling of the failure elements meets the determined tensile strength at cracking time. Table 1 shows the considered values.

TABLE 1: MATERIAL PROPERTIES OF CALCULATION MODEL

	RCC	CMC
Elastic modulus E_c in GN/m ²	28.8	34.4
Tensile strength f_{ctm} in N/mm ²	[-]	2.2

Following the calculation runs with activation of the failure elements were carried out. Due to comprehensive location of those failure elements, the most unfavourably spacing of

primary cracks can be determined. It amounts 6.85 m. Figure 5 shows the calculation result for this crack pattern.

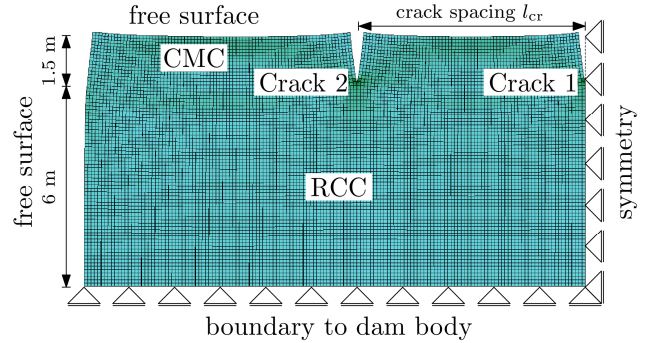


Figure 5: Authoritative distribution of geometric set primary cracks in the CMC-facing.

Required Minimum Reinforcement for 1.5 m thick CMC-facing of Diامر Basha Dam

As cracking in the CMC-facing is caused by bending restraint and occurs at material properties of hardened concrete, the restrained deformation in the form of crack opening of a primary crack at the CMC surface without any reinforcement has to be determined as following:

$$w_{rest,surface} = \frac{f_{ctm}}{E_{c,28}} \cdot l_{cr} = \frac{2.2}{34400} \cdot 6.85 \cdot 10^3 = 0.44 \text{ mm} \quad (5)$$

This exceeds the tolerable crack width of 0.2 mm, so that secondary cracks in the surrounding of the primary cracks have to be generated.

For compliance of crack width criteria in the primary cracks, their required number is:

$$n = 1.1 \cdot \left(\frac{0.415}{0.2} - 1 \right) = 1.32 \quad (6)$$

Nevertheless the result of n is not a whole number meanwhile only a whole-numbered quantum of secondary cracks can be generated, the calculation should be continued with its exact value. This ensures efficiency against the background of neglected reducing effects of residual stresses.

And with an assumed rebar diameter of 20 mm and 2 layers of horizontal reinforcement at the outer surface of CMC with a concrete cover of 7 cm the required minimum reinforcement to generate the described crack pattern amounts:

$$a_{s,req,surface} = \sqrt{\frac{20 \cdot 8^2 \cdot 100^2 \cdot 2.2}{0.2 \cdot 200000} \cdot (0.69 + 0.34 \cdot 1.32)} \quad (7)$$

$$a_{s,req,surface} = 28.3 \text{ cm}^2 / \text{m}$$

As the crack width at the inner surface of the CMC-facing is controlled by the bond in the transition zone between RCC and CMC, there is no additional reinforcement needed in this area. But with a view to the durability of the RCC surface, a constructional minimum reinforcement on the inner surface of the CMC-facing should be arranged. According to [5] this should be about:

$$a_{s,req,min} = \frac{f_{ctk,0.05} \cdot A_{ct}}{f_{yk}} \quad (8)$$

$$a_{s,req,min} = \frac{0,7 \cdot 2,2 \cdot 1.5 / 2}{500} = 23.1 \text{ cm}^2 / \text{m}$$

The required minimum reinforcement of the CMC-facing could be arranged as following:

outer surface of CMC:

horizontal: 1 layer Ø 20 mm - 10 cm	vertical: 1 layer Ø 20 mm - 15 cm
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inner surface of CMC:

horizontal: 1 layer Ø 20 mm - 15 cm	vertical: 1 layer Ø 20 mm - 15 cm
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The total amount of horizontal reinforcement amounts 52.4 cm²/m. The vertical reinforcement was chosen under constructive aspects, as there is no constraint in this direction due to small lift heights during concrete placing process. Furthermore this reinforcement is sufficient for restraint impacts during life cycle of the dam as well. The high restraint stresses in the CMC during winter period according to Figure 2 cannot appear in the pictured height, because of reduction of stiffness in the CMC after cracking and its accompanying reduction of hardening caused restraint stresses.

Conclusion

The main result of this investigation is a mechanically based approach for crack width control of impervious concrete facings out of conventional mass concrete (CMC) at the upstream surface of gravity dams out of roller compacted concrete (RCC).

This approach is based on the determination of the crack pattern due to the restraint in the CMC-RCC-compound system. Information about the restrained deformation was taken from a former investigation on this and the cracking process was simulated by a customized 2D-FEM calculation model - with the result of quantification of geometric set spacing of primary cracks.

Finally this allowed a mechanically based calculation of required minimum reinforcement under compliance of the deformation compatibility within the member.

The outcome of this approach is a saving of 25 % reinforcement amount in comparison to the result of a

conventional determination based on the cracking force according to [5]. This provides benefits on material costs and construction speed - especially due to the cancelling of the second layer of the horizontal reinforcement in the outer surface of the CMC-facing.

Although the approach is exemplified on a theoretical study for the Diامر Basha dam project in Pakistan, it is applicable in general.

However, as the underlying information about restraint in the CMC-RCC-compound system considers the influence of viscoelastic effects only with a smeared model, further investigation is needed at this point.

References

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