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Strength enhancement of precision concrete parts by sol-gel surface coating

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Abstract

In former own publications it was shown, that high precision concrete parts are a reliable alternative to natural stone for machine base frames. Beside long term stability also a predictable and highly reproducible thermal behaviour is required. The use of low expansion materials is not appropriate for a whole machine structure since these materials are coming with several drawbacks in the mechanical behaviour in combination with high costs. Thermal compensation by special design also raises cost and complexity. The application of materials with identical thermal expansion coefficients in combination with appropriate mechanical properties can solve this problem at significantly reduced costs. Concrete is a promising material for the whole machine structure under these circumstances.

In contrast to base frames moving parts need to have a lightweight design thus requiring a high level of specific stiffness. Concrete with a specific stiffness close to steel is an interesting material for the design of movable components coming up with dynamic properties comparable to welded steel structures. Additionally a high material strength is needed in lightweight design. Concrete shows high compressional strength but is sensitive to tensile stress that cannot be fully eliminated. Therefore notch effects and stress concentrations need to be avoided. Reinforcement by implementation of steel or carbon fibres is not applicable since they come with thermal inhomogeneity. An alternative reinforcement can also be done by organofunctional sol-gel silane coating.

Precision concrete, endurance strength enhancement, lightweight construction, organofunctional surface coating, coating simulation

1. Strength enhancement by sol-gel coating of concrete parts

The application of a tailor made glass coating with enhanced tensile strength implements compressive stress to the parts surface. Furthermore the tensile strength in the sol-gel-infiltrated zone is improved and surface micro damages are filled out. These three fundamental effect mechanisms and the coherences to the endurance strength are shown in the chart at figure 1. To verify the effect of the defect elimination, supporting factors as used in the German FKM Guidelines [1] can be applied beneficially. Since the measurement of internal stresses in the surface surroundings without taking effect to the internal stresses itself is not possible for concrete, the mathematical description of the stiffness improvement is a promising approach to verify the influence of the coating.

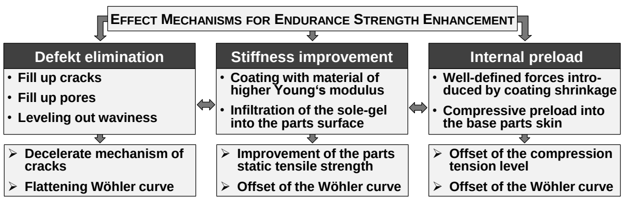

Figure 1. Effects for strength enhancement of sol-gel coated parts

The prediction of the endurance strength enhancement for functional coated concrete parts is based on a combination of calculated and experimentally derived data. Since the effects cannot be fully separated, the measurement data are influences by all effects and cross interactions. In this contribution a procedure for the implementation of physical properties and coating parameters for the prediction of the endurance strength enhancement is shown.

2. Methodology

For the endurance strength prediction of sol-gel coated concrete parts in lightweight design, the effective use of a practical FE-model method is helpful. First, the whole geometry has to be modelled and discretised into volume elements. The coating properties are then added by discretisation in form of coincident surface shell elements. The correlation of the derived displacements for the non-coated and the coated state are in correspondence to the reciprocal correlation of the strain level. With the relative strain level the prediction of the endurance strength enhancement for complex geometry is possible. To implement a simple shell element type for the description of the coated parts properties a substitute thickness T_{subst} and a representative Young's modulus E_{subst} needs to be introduced. The determination of these parameters is done based on a simplified prismatic beam model. The parameters are gained within the following three steps.

1. *Mathematical description of the physical properties*
2. *Experimental determination of measurable properties*
3. *Calculation of the remaining physical properties*

The composition and the inclusion of the chemical and physical properties of the unwrought sol-gel in the model is currently under process and not part of this paper.

3. Mathematical description of the physical properties

The mathematical description of the stiffness of a coated prismatic geometry is done by an analytic model using a variable Young's modulus over the cross section. The Young's modulus limits at the rim of the base part and at the outside of the sol-gel coating are unknown and not directly measurable.

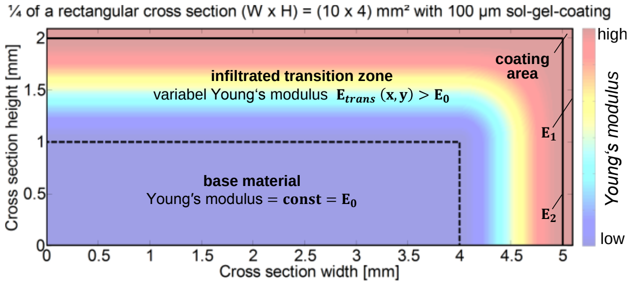

Figure 2. Young's modulus distribution in a rectangular cross section

An exemplary distribution of the Young's modulus in a rectangular cross section is shown in figure 2. Based on the estimation that the stiffness can't change abruptly over the position the stiffness change is expressed in form of a harmonic approximation as shown e.g. in figure 4 along the width.

The Young's modulus in the area limited by the dashed line is the base part Young's modulus E_0. The Young's modulus at the outside of the coating is called E_1. In the infiltrated transition zone the Young's modulus changes from E_0 to the maximum E_2 at the rim of the base part represented by the solid line.

The example beam is 10 mm in width W and 4 mm in height H. The measures of the coating influenced areas are the infiltrated depth RHT of 1 mm and the 100 µm wall ness T of the coating. The determination of E_1 and E_2 is explained in the following steps.

4. Experimental determination of measurable properties

The infiltrated depth is measured by SEM analytics of broken specimen cross sections. The coating thickness is determined by AFM. The dimensions W and H are represented by the mean value of 4 measures along the beams length L_0.

For the determination of E_1 and E_2 two independent measurement setups are necessary. The tensile load test and the 3-point flexure test yield two different values of the stiffness, which are independent because of the cubic term in the area of the moment of inertia.

The tests are executed with reproducible test specimen geometry of *DIN 50125 Form - E 4 x 10 x 35*. The specimens are fixed with special jaws, which allow non over constraint clamping. Also uncoated specimens of the same lot are used for the 3-point flexure test and the tensile load test for the determination of E_0. With the measures of the tensile stiffness $C_{tensile}$ and the flexure stiffness $C_{flexure}$ of the coated specimen the determination of E_1 and E_2 is enabled.

5. Calculation of the remaining physical properties

If all measured geometrical dimensions (B, H, T, RHT), the Young's modulus E_0 and the tensile / flexure stiffness are known, the determination of E_1 and E_2 can be done in the next step. For the exemplary solution $C_{tensile}$ of $50{,}52\ N/\mu m$ and C_{fexure} of $3{,}52\ N/\mu m$ are used.

5.1. Determination of the Young's modules E_1 and E_2

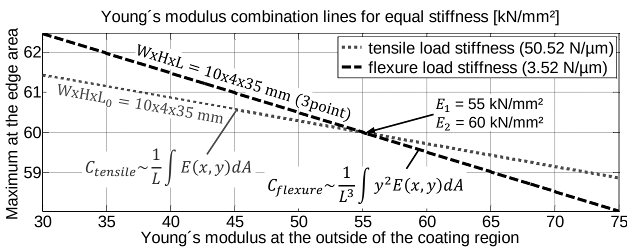

Figure 3. Determination of the Young's modules E_1 and E_2

Pairs of E_1 and E_2 calculated by the analytic model are shown in figure 3. The plotted lines represent combinations with equal stiffness to the tensile and flexure tests. The point of intersection is the combination, which could be assumed for the calculation of the substituting shell element properties for the FE-Model. The calculated E_1 and E_2 could be higher than the actual stiffness, because the measured tensile and flexure stiffness's are including all reinforcing effects of the coating.

5.2. Determination of the properties E_{subst} and T_{subst}

As the representative Young's modulus E_{subst} the maximum value at the base parts rim E_2 is used. T_{subst} is determined by the integration of the differential stiffness along an orthogonal path to the parts rim across the infiltrated transition zone and the coating region. The progression of the Young's modulus is shown in figure 4. The grey area under the graph represents the sol-gel-induced stiffness enhancement.

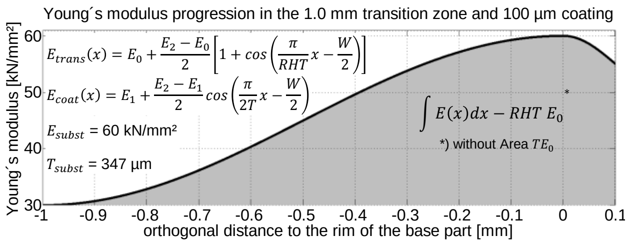

Figure 4. Determination shell element properties E_{subst} and T_{subst}

The achieved stiffness enhancement in relation to a pure concrete specimen takes about 47% for the tensile load and 96% for the flexure loaded case. The stiffness enhancement for complex light weight design parts is somewhat smaller, since the wall thickness relation of the base part and the coating is higher than the assumed relation in the shown example.

6. Enhancement of the endurance strength

With the surface shell elements the stiffness solution of complex light-weight geometry with sol-gel coating with the representative shell elements could be done in a very easy way.

The minimum enhancement of the endurance strength is the offset of the Wöhler curve caused by the changed relative strain level. The endurance strength enhancement could be defined by the factor X shown in figure 5.

$$\boxed{X = \frac{N_{coated}}{N_{uncoated}} = \left(\frac{\sigma_{coated}}{\sigma_{uncoated}}\right)^{-k}} \longrightarrow C \sim \frac{1}{\sigma} \longrightarrow \boxed{X = \left(\frac{C_{uncoated}}{C_{coated}}\right)^{-k}}$$

N = cycles to failure | k = Wöhler coefficient | σ = strain | C = stiffness

Figure 5. Endurance strength enhancement factor X [2]

Furthermore the flattening of the Wöhler curve leads to even higher endurance strength. This effect has to be investigated experimentally in dynamic tests. The consideration of this effect could be done with a customized Wöhler coefficient.

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