STRENGTHENING OF EXISTING STRUCTURES USING R-UHPFRC: PRINCIPLES AND CONCEPTUAL DESIGN

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Abstract

The addition of a layer of strain-hardening UHPFRC to an existing member in reinforced concrete (RC) has proven to be an effective method to increase the structural resistance and durability of concrete structures [1-3]. This paper is intended for structural engineers willing to use UHPFRC to strengthen existing structures. The basic idea of the UHPFRC strengthening method is introduced. The conceptual designs for the improvement of two large highway viaducts are presented and their feasibility is validated by means of simple analytical formulas.

Résumé

L'addition d'une couche de BFUP écrouissant pour renforcer des éléments en béton armé a déjà fait ses preuves comme méthode efficace pour augmenter la résistance et la durabilité des structures en béton [1-3]. Cet article s'adresse à des ingénieurs désirant utiliser le BFUP pour renforcer des structures existantes. L'idée de base de la méthode de renforcement avec du BFUP est introduite. Les approches conceptuelles pour améliorer deux grands viaducs autoroutiers sont présentées et leur faisabilité est validée par des formules analytiques simples.

1. INTRODUCTION

"UHPFRC" stands for Ultra-High Performance Fibre Reinforced Cementitious Composite material produced from cement and other reactive powders, additions, hard particles, water, admixtures and high amount of relatively short steel fibres. UHPFRC does not comply with the definition of "concrete" in standards, and therefore, UHPFRC should not be called "concrete" as is evident from Figure 1a. It is fundamental to understand UHPFRC as an independent material and technology with specific properties and features. This is the first basic principle when designing with UHPFRC to improve existing structures.

The second principle is that UHPFRC shall be complemented in a targeted manner with reinforcing steel in order to enhance structural performance and economy of structural applications. Subsequently, the terms reinforced UHPFRC (or short: R-UHPFRC) are used.

a) b)

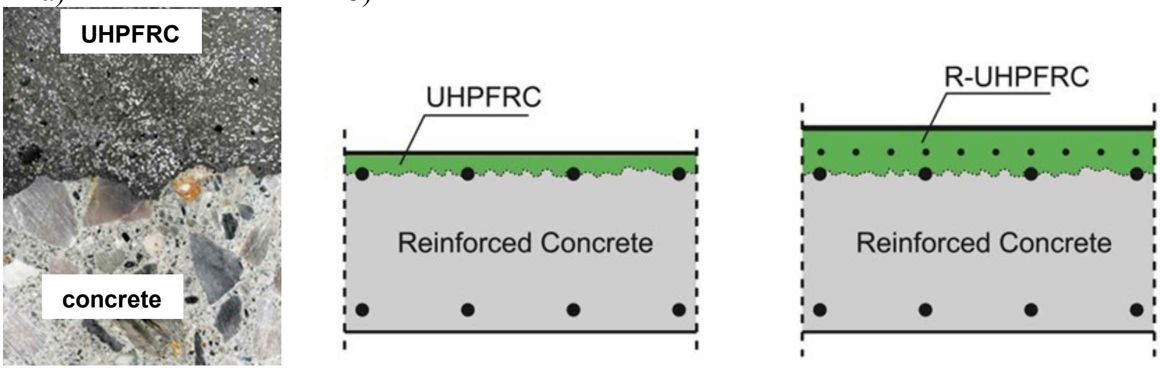

Figure 1: a) UHPFRC – concrete core showing the obvious difference between the two materials; b) Basic configurations of structural elements combining UHPFRC and RC: left: UHPFRC layer (25 to 40mm) has a protective function only; right: R-UHPFRC layer (40 to 80mm or more) has both structural resistance and protective functions.

Reinforced concrete (RC) structures like bridges, retaining walls or buildings often show insufficient performance in terms of structural resistance and durability when exposed to severe environmental influences and high mechanical loading. Interventions to improve deteriorated concrete structures are a heavy burden from the socio-economic viewpoint since they lead to significant intervention costs and user costs. (RC structures are cheap at construction but turn out to be costly during their use because of premature interventions.)

Many conventional "retrofitting" using concrete and repair mortar are not durable, and therefore, novel concepts for the improvement of RC structures must be developed. The addition of a thin layer of strain-hardening UHPFRC to an existing member in reinforced concrete (RC) has proven to be an effective method to increase the structural resistance and the durability of existing RC structures. The two basic concepts are shown in Figure 1b; they lead to the structural system of composite R-UHPFRC – RC elements.

2. PERFORMANCE OF UHPFRC

The required performance of currently used strain-hardening UHPFRC is summarized in [1-3]. Other fibre reinforced cementitious materials with lower performance – also designated as "UHPC" or "UHPFRC" – do not qualify for the designs and applications described in this paper.

The tensile behaviour of strain-hardening UHPFRC is of first importance for strengthening purposes presented in this paper. The uniaxial tensile behaviour of plain UHPFRC has to comply with the indications and values given in Figure 2a. The significant strain-hardening deformation ε_U of more than 2‰, while the (uniaxial) tensile strength f_{Ut} reaches values ranging from 8 to 14 MPa, can only be obtained with fibre contents of more than 3 volume-% of straight steel fibres with an aspect ratio of at least 65.

The main reasons to complement UHPFRC with steel reinforcing bars to obtain R-UHPFRC are a significantly improved tensile behaviour and reduced scatter of UHPFRC properties [4, 5]. Small diameter steel reinforcing bars (arranged with relatively small spacing) provide in-plane continuity to the UHPFRC layer and ensure its monolithic action with the RC element in flexural members. The rebars not only significantly increase the resistance but also improve the deformation capacity and strain-hardening behaviour of UHPFRC. The global tensile behaviour of R-UHPFRC is described by linear superposition of the reinforcing steel and the UHPFRC tensile behaviours (Fig. 2b).

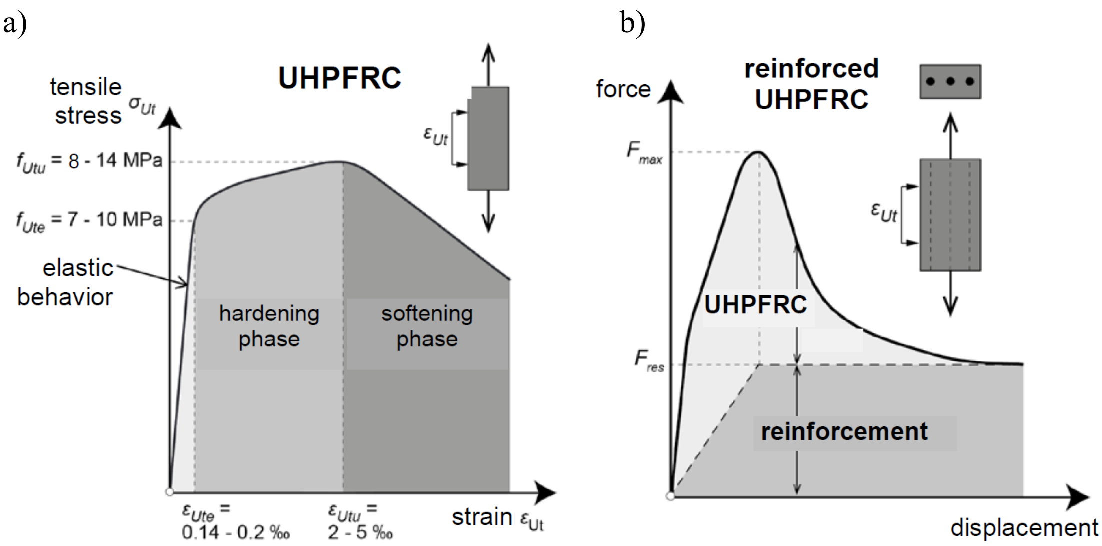

Figure 2: Characteristic tensile behaviour of a) plain UHPFRC and b) R-UHPFRC

Relatively modest UHPFRC compressive strength of 130 MPa is generally sufficient in the context of the present strengthening concept. The modulus of elasticity of UHPFRC in tension and compression is 45 to 50 GPa which is not significantly higher than the one of concrete. For composite R-UHPFRC – RC members, this is advantageous with respect to deformation-induced stresses due to temperature and shrinkage effects.

UHPFRC has extremely low permeability and water conductivity due to the extremely dense matrix making strain-hardening UHPFRC impermeable for liquids, crack-free under service conditions and thus durable.

3. STRUCTURAL RESPONSE OF R-UHPFRC – RC COMPOSITE BEAMS

The author and his team have investigated the structural concept of composite R-UHPFRC – RC elements (Fig. 1b) over more than 17 years (see [1] and references in [2, 3]).

3.1 Behaviour in bending

When in tension, the R-UHPFRC layer principally acts as an added flexural reinforcement for the RC element. Both the steel rebars and the UHPFRC contribute to the resistance. RC beams strengthened with an R-UHPFRC layer are characterized by a significant increase in elastic stiffness and ultimate resistance.

The bond between UHPFRC and concrete is obtained by preparing the concrete substrate surface by high pressure water jetting or sand blasting. This surface preparation is sufficient to obtain full bond between UHPFRC and concrete. In fact, pull-out fracture tests (force applied perpendicular to the surface) show the expected fracture in the concrete substrate (and not at the interface or in the UHPFRC). Thus, the composite R-UHPFRC – RC section is monolithic.

The plastic post-peak rotation capacity of strengthened RC beams is maintained with an appropriate design of the rebars in the UHPFRC layer. Also, smooth high yield strength reinforcing bars in the UHPFRC layer offer high increase in resistance while the post-peak rotation capacity remains ductile. The structural behaviour in terms of moment – curvature relation and the ultimate bending moment are calculated using the conventional sectional model with the extension to account for the R-UHPFRC layer in the monolithic section (Fig. 3).

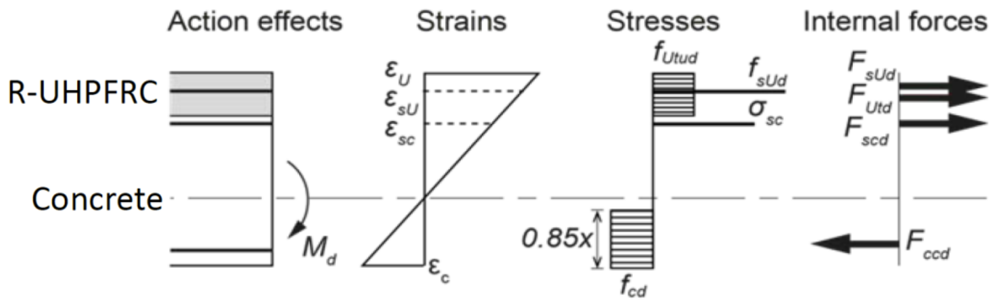

Figure 3: Plane section analysis for bending resistance at Ultimate Limit State ULS.

When subjected to compressive stresses, the R-UHPFRC layer acts as a compression flange but the high UHPFRC compressive strength cannot be fully exploited. This is because the compressive strength of the adjacent concrete below the UHPFRC layer often is 3 to 6 times lower, and thus concrete would crush before UHFPRC reaches its strength.

3.2 Behaviour in combined bending and shear

As was shown by tests on composite beams, the addition of a layer of UHPFRC delays the formation of the inclined shear crack in the concrete section. For many geometric configurations, the layer of UHPFRC modifies the failure mode from shear failure with little deformation to a ductile flexural failure mode.

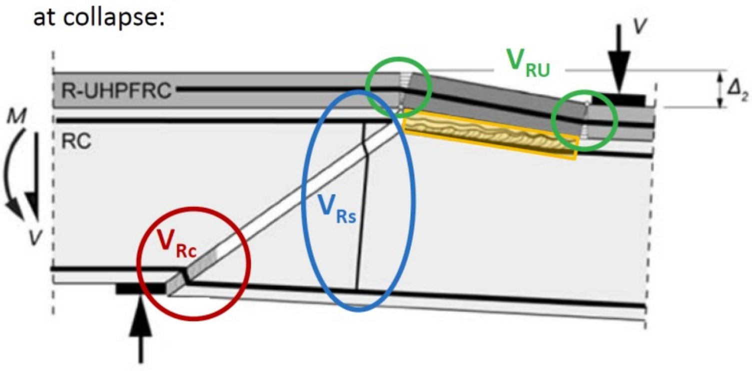

Figure 4: Shear failure mechanism at ULS

A shear failure is observed in a composite section only for specific geometric and material configurations. Due to the experimentally observed failure mechanism (Fig. 4), the ultimate shear strength is composed of the contributions due to (1) concrete web crushing V_{Rc}, (2) vertical steel reinforcement yielding V_{Rs} and (3) the two hinge-bending mechanism of the R-UHPFRC layer V_{RU}. Accordingly, analytical expressions have been deduced to calculate the ultimate shear strength [6, 7].

3.3 Fatigue behaviour

The results of bending fatigue tests on R-UHPFRC – RC beams revealed the existence of a fatigue limit at 10 million cycles at a fatigue stress level of about 50 % of the ultimate static resistance of the R-UHPFRC – RC beams [8]. Consequently, fatigue design rules for R-UHPFRC – RC members under bending fatigue need to account for steel rebar and UHPFRC fatigue resistances. Fatigue stresses are calculated using an elastic sectional model similar to the one shown in Figure 3.

4. TWO APPLICATIONS

4.1 Introductory remark

In Switzerland, the technology of strengthening of existing RC structures by a layer of R-UHPFRC was applied for the first time in October 2004. Since then, more than 50 structures have been strengthened using this technology. Subsequently, the conceptual design for two large highway viaducts is presented.

4.2 Improvement of the Chillon Viaducts [9]

4.2.1 Motivation and objective

Located in Switzerland, the Chillon viaducts are two parallel posttensioned concrete highway bridges built in the late 1960s (Fig. 5). To insure structural safety for future traffic demands, it was decided to strengthen the slab by adding a layer of R-UHPFRC acting as an external tensile reinforcement for the slab and main girder.

Figure 5: Chillon Viaducts along Lake Geneva.

4.2.2 Conceptual design

The concept implemented in 2014/15 consisted in casting one layer of R-UHPFRC on the deck slab (Fig. 6) to achieve the following beneficial effects:

- increase the slab's ultimate (bending and shear) resistance in the transverse direction
- increase the slab's stiffness to reduce fatigue stresses in steel rebars in the concrete
- increase the hogging bending moment resistance and the stiffness of the box girder
- provide waterproofing to protect the existing concrete of the slab from water and chloride ingress, thus improving durability
- limit duration of the intervention.

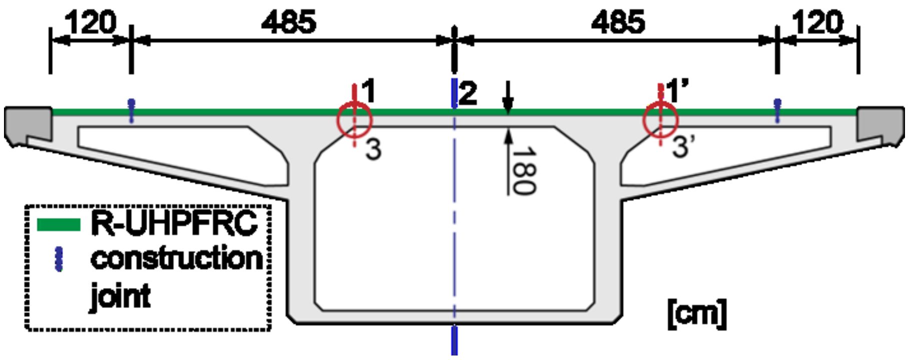

Figure 6: Geometry of the box girders cross-section (thickness of R-UHPFRC layer: 50mm over piers and 40mm in the spans).

4.2.3 Pre-dimensioning

As illustrated in Figure 6, the concrete bridge deck slab has a total thickness h_c of 180 mm. The transversal 16-mm diameter top steel rebars are positioned at a height d_{sc} of 152 mm from the intrados and spaced at 125 mm. There is no transversal pre-stressing in the bridge deck slab. The layer of UHPFRC has a thickness of h_U of 40 mm and is reinforced transversally with 12-mm diameter rebars also spaced at 125 mm. The centre of these rebars is at 16 mm from the top of the concrete. Over the piers, the thickness of the UHPFRC layer was increased to 50mm, and 12 mm rebars spaced at 125mm were placed in the longitudinal direction (in addition to the transverse rebars) to increase the negative (hogging) moment resistance of the box girder in the longitudinal direction.

The *transversal bending resistance of the deck slab* was calculated using the resistance model according to 3.1. For negative bending moment, the ultimate bending resistance m_{Rd} for sections 1 and 1' (Fig. 6) is equal to 165.5 kNm/m. The ultimate bending resistance of the strengthened slab is 73% higher than the resistance of the RC section alone. For positive bending moments, the layer of UHPFRC is in compression and mainly contributes to the resistance by reducing the height of the compression zone and thus increasing the static height. The ultimate positive bending resistance at section 2 is increased by 33%.

The deck slab does not have any shear reinforcement. *Ultimate shear resistance* v_{Rd} of the composite element was thus calculated as the sum of the concrete contribution v_{Rc} and the UHPRRC contribution v_{RU} according to Chapter 3.2. With an angle of the inclined crack estimated at 35°, the shear resistance of the composite slab section is 265 kN/m. The UHPFRC layer contributes to 33% of the total shear resistance. Due to the R-UHPFRC reinforcement, the increase in shear resistance is 40% according to the resistance model presented in [7].

The increased shear resistance is significantly higher than for the flexural failure mode, and the flexural failure mode is much more likely to occur even in shear prone loading situations.

4.2.4 Execution

All listed requirements and structural functions were realized by the casting of just one layer of R-UHPFRC using a machine (Fig. 7) on the concrete surface prepared by removal of 10mm by hydrojetting. The large volume of 2'350m^3 of fresh UHPFRC was produced on-site in a ready-mix plant. During the summers 2014 and 2015, the UHPFRC layer was cast over the two 2'120 m long viaducts, each in less than 30 working days.

Figure 7: UHPFRC casting machine (left) and fresh UHPFRC layer after casting (right)

Testing according to quality assurance given in [1] revealed that the UHPFRC complied with the requirements for strain-hardening UHPFRC. The fresh UHPFRC had to show thixotropic behaviour as it was cast on slopes of up to 7%. An asphalt layer and bituminous pavement, overall 6-cm thick, were finally placed on the UHPFRC surface to obtain the drivable road surface. The overall self-weight of the structure was not increased significantly.

4.3 Improvement of three highway viaducts consisting of multi PC precast girders

4.3.1 Motivation and objective

Three 45 years old highway twin viaducts of identical construction follow each other in a hilly area in Central Switzerland to form a total length of 1'050m (Fig. 8a). The superstructure of the viaducts is composed of four slender precast prestressed girders with lengths of 38 m, 40 m or 42 m. These girders have been designed as simple span beams, but during construction, they were monolithically joined over the piers (to avoid joints) to form a continuous girder.

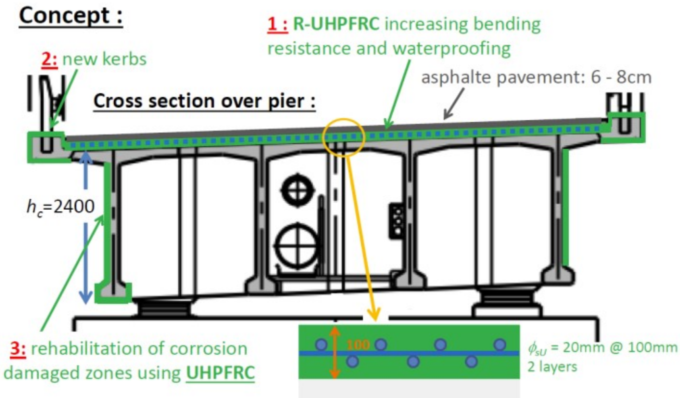

Fig. 8 a) View of one of the three twin viaducts; b) Intervention concept (cross section at pier)

The realized hogging moment capacity (over the piers) is relatively low. In view of future traffic demands, the viaducts need to be strengthened to increase the load bearing capacity. They also need to be rehabilitated because of rebar corrosion damage.

4.3.2 Conceptual design

The basic idea of the strengthening of the superstructure is the following: since the original hogging moment capacity is low, it can be increased significantly by adding a strong R-UHPFRC layer on top of the slab (Fig. 8b). Allowing for plastic moment redistribution from mid-span (sagging moment range) to the piers (hogging moment range) at ULS, the required load bearing capacity of the superstructure is obtained. This moment distribution is however only possible if the relevant cross sections allow for plastic hinges of sufficient ductility that has been verified in the present case.

The 100 mm thick R-UHPFRC flange extends by 6 m on each side of the pier such that the strong R-UHPFRC layer also increases the shear resistance of the girder near the piers according to the mechanism shown in Fig. 6.

The rest of the deck slab (sagging moment region) is strengthened by a 45 mm thick UHPFRC layer with rebars in the transverse direction such as to increase the torsional stiffness of the open cross section allowing for more effective distribution of high concentrated forces in the transverse direction of the cross section while reducing moment peaks.

In addition, the UHPFRC layer on the deck slab provides the waterproofing, and UHPFRC is also used to rehabilitate local rebar corrosion damage on the outer girders and bottom flanges because of superior performance compared to repair mortars.

4.3.3 Pre-dimensioning

Bending moment capacity: With design values for the tensile strength of UHPFRC and steel rebars of respectively 8 MPa and 435 MPa, and the UHPFRC cross section and rebar area as given in Figure 8b, the tensile force developed at ULS by the R-UHPFRC flange is F_{RUd} = 3'480 kN per meter width. (78% of this tensile force is due to the steel rebars; 22% is due to the UHPFRC.) The internal lever arm y_U of the cross section (i.e. distance between the resultant tensile force and compression force), plastified at ULS, is estimated to be about 1.8 m, and thus, the additional hogging (negative) moment capacity in the longitudinal direction is: $\Delta M_{RUd} = y_U \cdot F_{RUd} = 1.8m \cdot 3.48MN = 6.3MNm/m$.

This additional moment capacity is sufficient to obtain the required moment bearing capacity of the superstructure. Obviously, increasing the tensile reinforcement leads to higher compressive stresses in the lower part of the cross section over the pier. In the present case, the compression zone was not fully exploited before strengthening and the compressive strength increased over time to reach after 45 years a compressive strength about 30% higher than the 28-day-compressive strength assumed in the initial design. These are the reasons why the dimensions of the compression zone are sufficient also after strengthening.

Shear resistance: The resistance model (Fig. 4) was applied to the 2.5m high girder. The following contributions to the ultimate shear resistance of one strengthened girder was obtained: (1) concrete web crushing V_{Rc} = 426 kN; (2) two hinge mechanism of the R-UHPFRC layer V_{RU} = 305 kN; (3) steel reinforcement: vertical rebars (stirrups) and vertical component of two inclined post-tensioning cable in the concrete girder web: V_{Rs} = 813 kN. Thus, the ultimate shear resistance of the strengthened girder is the sum of (1) to (3): V_{Rd} = 1'544 kN. This ultimate shear resistance is 90% higher than the ultimate resistance before strengthening and 34% higher than the acting shear force. Actually, the shear resistance is enhanced to such an extent that bending failure will prevail. In addition, non-linear FE analysis was performed confirming the formation of the expected failure mechanism and the analytically determined ultimate shear resistance.

Slab strengthening in the transverse direction: The R-UHPFRC layer leads to a thicker slab of higher stiffness allowing for more effective transverse distribution of concentrated loads. This favourable effect was considered and precisely determined in the detailed dimensioning.

The pre-dimensioning was used to validate the feasibility of the intervention concept. Detailed design by means of non-linear FE analyses gave deeper insight into the performance of the R-UHPFRC strengthening concept.

4.3.4 Execution

The works to improve the three viaducts will be conducted from 2017 to 2019. In 2017, suitability tests will be performed to validate the UHPFRC material, the procedure to rehabilitate the zones showing rebar corrosion damage and the machine-made UHPFRC casting. UHPFRC will be cast on the deck slab in 2018 and 2019.

5. CONCLUSIONS

- The strengthening method using a layer of strain-hardening UHPFRC is an effective method in terms of technical performance. Significant tensile strain-hardening and high tensile strength of the UHPFRC is required for the improvement of concrete bridges.
- The design of the strengthening intervention is based on a clear concept with a targeted consideration of the structural behaviour and performance of the given structure to be improved as well as the UHPFRC material properties.
- The UHPFRC strengthening concept has been demonstrated by means of two large viaducts of common design, i.e. box girder and multiple beam cross sections. Simple analytical formulas are sufficient to validate this intervention concept.

The presented R-UHPFRC technology to improve the resistance and durability of existing concrete structures is cost-effective at execution and economic. Actually, lower intervention costs (when compared to traditional methods) are the main reason for the increasing number of applications of the R-UHPFRC technology in Switzerland.

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