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Performance Evaluation and Technical Limitation Analysis of UHPC Strengthening Technology for Typical Building and Bridge Structural Components

Tiancheng Lai[1, a]

[1]School of Artificial Intelligence and Intelligent Manufacturing, Jiangsu University, Zhenjiang, 212013, China

[a]1195953677@qq.com

Abstract

Fatigue, chloride erosion and seismic loading act together over time to damage reinforced concrete structures gradually; thus, effective retrofits are required. Ultra-High Performance Concrete (UHPC) has good properties such as high strength, strain-hardening toughness, low permeability and excellent compatibility with normal concrete, so it is suitable for this purpose. Based on the above, this paper presents a data-driven comparison of recent experimental and numerical studies on UHPC retrofitting for beams, columns, frames, masonry-infilled frames, corroded piers and box-girder bridges. Systematically evaluate the above indicators of strengthening efficiency, failure modes, parameter sensitivities and engineering applicability. Based on the above analysis, UHPC-based composite systems have shown better performance than traditional single-retrofit methods in terms of increased bearing capacity, seismic energy dissipation and fatigue resistance. However, some serious problems still exist, such as prominent parameter threshold effects, inherent joint defects in prefabricated systems, severe on-site construction constraints, and a significant lack of multi-factor coupled experimental verification. The above results provide experimental references and design ideas for optimisation and standardisation of UHPC retrofitting in infrastructure rehabilitation.

Keywords

Ultra-high-performance concrete (UHPC); Retrofitting; Reinforced concrete; Seismic performance; Flexural strengthening; Bridge engineering; Prefabricated structures; Structural rehabilitation.

1. INTRODUCTION

In-service reinforced concrete (RC) buildings and bridges are increasingly susceptible to deterioration under the coupled effects of fatigue loading, chloride ingress, and seismic actions. Typical distresses—flexural cracking and stiffness degradation in beams, compression damage in columns, residual drifts in frames, and insufficient transverse integrity of bridge decks—continuously undermine structural safety and serviceability. Conventional retrofitting techniques, including section enlargement, steel plate bonding, and FRP wrapping, have inherent limitations:FRP systems are susceptible to interfacial debonding under cyclic loading without ductile deformation gain [1]; cementitious repair materials frequently have poor compatibility with old concrete and cause secondary cracking [2]; and cast-in-place methods require extended curing and complicated formwork, thus being unsuitable for quick repair [3].

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Ultra-high performance concrete (UHPC) is a good choice; it has high compressive/tensile strength, strain-hardening toughness, a dense microstructure, and excellent bond compatibility with normal concrete, so the problems of interfacial and durability failure in traditional materials can be solved effectively. Recently, many studies have been conducted on UHPC-based retrofits at various levels. CFRP-reinforced UHPC overlays can be used to increase the load-bearing capacity and ductility of damaged RC beams [1], and full UHPC encapsulation can restore the stiffness and fatigue resistance of pre-damaged T-beams [2] for bridge girders. Prefabricated FRP-UHPC blocks have improved the column compressive strength of building structures [3], and U-shaped UHPC jackets and diagonal strips have shown good results in the seismic rehabilitation of frames and masonry-infilled structures [4-6]. Applications of bridges have also been extended to suspension deck overlays with optimised casting sequences [7], seismic restoration of corroded piers by UHPC shells [8], and transverse stiffening of box-girder bridges [9].

Although the above have been achieved, the current knowledge base is still disjointed. Most research has focused on individual analyses of a single scheme for a particular part, and no all-encompassing, quantitative comparison among various retrofitting plans has been conducted. In addition, there are recurrent technical bottlenecks, such as significant parameter threshold effects, joint deficiencies in prefabricated systems, constructability constraints, and a severe lack of multi-factor coupled experimental data; these have not yet been addressed by a unified engineering system. The above problems have prevented the widespread application and development of UHPC strengthening technology.

Given the above deficiencies, this paper will systematically summarize recent experimental and numerical studies on UHPC retrofitting for representative RC building and bridge elements. Quantitatively assess the strengthening effect and failure mode; explore how various design and construction factors affect them; identify general technical obstacles that limit actual implementation; and propose specific research directions for future optimisation. The results aim to offer a strong theoretical basis and practical design ideas to promote the standardised application and continuous development of UHPC-based rehabilitation in civil engineering.

2. UHPC STRENGTHENING PERFORMANCE AND MECHANISM OF RC BEAM COMPONENTS

RC beams are used to support the load of buildings and bridges. Due to extended exposure to vehicle-induced fatigue loads, environmental corrosion and continuous static stresses, these components often suffer from progressive bending cracks, stiffness reduction and cumulative fatigue damage; thus, their service life and structural safety have been significantly reduced. Fig. 1 shows a general division of UHPC strengthening methods for RC building and bridge elements, including beam reinforcement, column and frame reinforcement, and bridge component strengthening (refer to Fig. 1).

2.1. Flexural Performance of CFRP-Reinforced UHPC Composite Overlay Strengthening

Plain UHPC overlay strengthening provides little enhancement; only an increase of 8%-11% in the ultimate flexural capacity of damaged RC beams was achieved, and severe localised cracking occurred in the UHPC layer at failure [1]. Therefore, a CFRP-reinforced UHPC composite overlay has been developed to address this problem. The system cooperatively distributes the load between CFRP reinforcement and UHPC matrix to enhance the ultimate flexural capacity by 179%-183% and increase energy dissipation by 2.34-2.63 times compared with unstrengthened beams [1]. CFRP fibres serve as crack-bridging and stress-transfer devices to prevent large-scale cracking and thus avoid brittle fracture of plain UHPC overlays.

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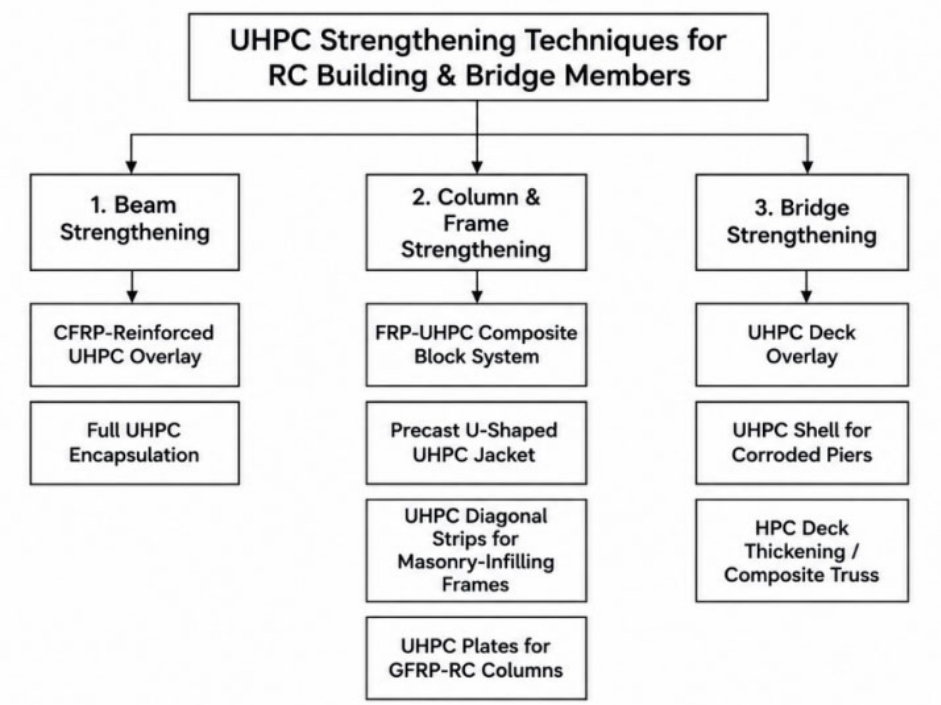


Figure 1. Classification of UHPC strengthening techniques for RC building and bridge components.

Interfacial Bonding at the interface of UHPC overlay and old concrete substrate affects composite behaviour. Good Surface Preparation should be carried out to eliminate interfacial voids and slippage, and compatibility of deformation needs to be ensured [1]. Increasing the thickness of the overlay alone will not result in a continuous improvement; instead, the combination of CFRP configuration and UHPC thickness needs to be optimised for reinforcement effect.

2.2. Fatigue and Ultimate Performance of Full UHPC Encapsulated Bridge T-Beams

Bridge T-beams under repeated vehicle loads are susceptible to cumulative fatigue damage, stiffness reduction and residual deformation. Full UHPC encapsulation has been used successfully on fatigue-damaged T-beams. Pre-damaged T-beams strengthened with full UHPC encapsulation were tested in previous experiments at a load amplitude of 25% of the ultimate load, and after 1.576 million loading cycles, there were no visible cracks and only a 12.22% decrease in stiffness [2].

Full UHPC encapsulation was used in the final flexural test to restore the flexural capacity of the damaged T-beam to 529 kN·m from 155 kN·m and increased the initial stiffness by approximately 14 times [2]. Sandblasting and a mechanical connector are used together to enhance the bond at the interface and prevent debonding and slippage. Full encapsulation requires a large amount of construction space around the beam, which is often not available for in-service bridges. In addition, fully enclosed beams may develop concentrated mid-span cracks under severe loads; therefore, longitudinal reinforcement inside the UHPC layer can induce distributed cracking and increase the safety margin [2].

3. PREFABRICATED UHPC STRENGTHENING TECHNOLOGY FOR COLUMNS AND FRAME STRUCTURES

Prefabricated UHPC composite strengthening offers significant advantages over traditional cast-in-place methods—factory fabrication, rapid assembly, shorter construction periods, and

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more consistent quality—and has increasingly become a mainstream solution for seismic rehabilitation and compressive performance upgrading of building components. Based on existing studies, typical prefabricated UHPC systems fall into three categories:FRP-UHPC blocks for columns, U-shaped jackets for frames, and UHPC plates for GFRP-RC columns are all different in terms of mechanism and application.

3.1. Compressive Performance of FRP-UHPC Composite Strengthened RC Columns

Older RC columns generally have a small axial capacity, eccentricity resistance and lack ductility. A prefabricated UHPC block system and external FRP wrapping can be used to address the above problems [3]. Therefore, no on-site formwork or curing is required, and the process will be more efficient. According to the test results, the composite system has increased the axial capacity by 405% and the eccentric capacity by 658% over unstrengthened columns [3] (see Fig. 2).

Control of the thickness of FRP wrapping and embedded FRP strip configuration for compressive strength and failure mode. Adding more FRP layers can enhance the post-peak ductility and deformation capacity, and embedded strips are also effective at countering tensile deficiency in the tension region under eccentric loading [3]; however, all previous tests have been conducted on small-scale models, and full-scale verification has yet to be performed.

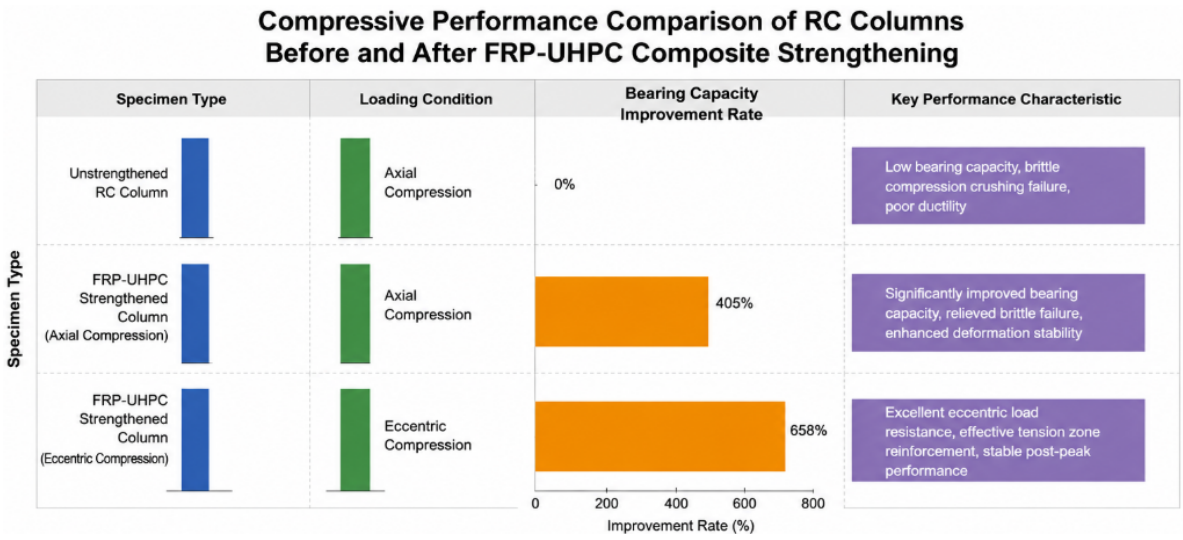


Figure 2. Enhancement of compressive capacity of RC columns strengthened with FRP-UHPC composite system.

3.2. Seismic Performance of Precast U-shaped UHPC Jacket Strengthened RC Frames

Seismic damage in RC frames includes residual deformation, stiffness reduction and decreased energy dissipation; they are difficult to repair by conventional means. A precast U-shaped UHPC jacket with reserved connecting bars can be quickly assembled at the construction site and connected to the original frame [4]. Cyclic tests have shown that after reinforcement, the peak capacity has risen by 70%, the initial stiffness has increased by about 960% (from 116 to 1,228 kN/mm), and the total energy dissipation has almost tripled [4]. The improved frame has good stability at a 8% drift (test end), and there is no debonding, spalling or collapse. However, the previous yielding of the original steel bars results in increased residual drift due to bar slip under cyclic loading; thus, this is a design problem [4].

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3.3. Performance of Seismic Retrofitting for UHPC-Strengthened GFRP-Reinforced Concrete Columns

GFRP-RC columns are frequently used in corrosive environments, and they have limited post-earthquake repairability because of a different bond and elastic behaviour of GFRP bars. Precast UHPC plates alone increase the peak capacity by 43.2%, and the UHPC + NSM combination enhances the capacity by 76%-79% [5]. UHPC strengthening does not uniformly enhance the ductility of GFRP-RC columns; premature NSM debonding can reduce it (e.g., ductility decreased from 4.44 to 3.20 in one specimen) [5]. Strengthening increases the position of the plastic hinge above the column base, and the UHPC plates remain undamaged; thus, good seismic performance and column protection have been achieved [5]. A new flexural capacity formula based on section equilibrium has been derived to predict the test column's capacity within 10 per cent.

3.4. Seismic Performance of UHPC Diagonal Strip Strengthened Masonry-Infilled RC Frames

Masonry-infilled frames are prone to diagonal cracking, corner crushing, and out-of-plane instability under seismic loading. Prefabricated UHPC diagonal strips outperform an enhanced CFRP scheme with mechanical anchors:Lateral capacity is about double that of unstrengthened frames and around 26 per cent higher than that of CFRP-strengthened frames [6]. A 10mm-wide strip has performed well; it has a relatively high peak strength (only 3.6% lower than a 20mm-wide strip), similar energy dissipation (7.9% lower), no buckling, and higher ductility; its cumulative energy dissipation is three times that of an unstrengthened frame [6]. Thickening to 20 mm will have uneven stiffness and out-of-plane buckling. The epoxy-filled joint of the UHPC plate is a weak link, and cracking starts here; the UHPC-to-masonry interface remains undamaged [6]. Joint vulnerability will be addressed in the next round of optimisation.

4. UHPC STRENGTHENING TECHNOLOGY FOR BRIDGE STRUCTURAL COMPONENTS

Bridge structures are subjected to various loads and harsh environments, and the main types of performance-limiting defects are deck cracking, pier seismic damage and insufficient transverse integrity. Bridges need to be built quickly and are also required to be fatigue-resistant and durable. UHPC strengthening has gradually been applied to bridge rehabilitation, and now several representative cases have been realised, such as suspension deck overlays, corroded pier seismic retrofitting, and box-girder transverse stiffening. This section will introduce the construction adaptability, mechanism and limitations of UHPC in these circumstances.

4.1. Construction Optimisation and Crack Control for UHPC Bridge Deck Overlay

Long-span suspension bridges have low stiffness and considerable deformation coupling during construction. A single cast-in-place UHPC deck overlay will produce tensile strain in the fresh UHPC due to its own weight and may cause early-age cracking. Therefore, a simple mechanical analysis method was proposed and employed to optimise the casting sequence [7]. Among the three schemes, the mid-span-to-ends sequence has lower tensile strain and thus reduces the risk of early-age cracking by 71.8% and 50.5% compared with the end-to-end and ends-to-mid-span schemes, respectively [7]. It has been applied successfully to the reconstruction of the Yichang Yangtze River Bridge and offers a reference for other similar projects.

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4.2. Seismic Performance Restoration of Chloride-Corroded RC Bridge Piers Strengthened by UHPC Shells

Coastal bridge piers have been damaged by chloride-induced corrosion, cover spalling and material degradation, and thus have reduced seismic capacity. A numerical model of UHPC shell-strengthened corroded piers was built to investigate the impact of shell thickness, corrosion life and axial compression ratio [8]. Based on the above results, UHPC shells can meet the demand for seismic performance of piers with up to 70 years of corrosion damage. A 30 mm shell can compensate for corrosion-induced losses; at 70 years old, the residual yield and peak force are 1.013 and 1.017 times that of uncorroded piers [8]. Increase the capacity and energy dissipation by adding a thicker shell and increasing the axial compression ratio. A relatively large axial compression ratio will cause post-peak degradation, and UHPC shells cannot correct for this. Most of the current studies are numerical; full-scale tests and field validations under multiple-factor coupling have yet to be conducted [8].

4.3. Improvement of transverse integrity for UHPC-strengthened box-girder bridges

Early box-girder bridges without transverse diaphragms often have insufficient transverse stiffness and non-uniform load distribution, resulting in wet joint cracking and stiffness loss over time. Five strengthening schemes were proposed and evaluated for the feasibility of high-performance cement-based reinforcement [9]. For undamaged bridges, the HPC deck thickening scheme is most suitable; it can improve the uniformity of load distribution by 82.94% and reduce deflection by 47.91% [9]. Composite truss schemes have a relatively low sensitivity to damage and good long-term stability for damaged bridges. Based on the above results, select and design UHPC transverse strengthening for box-girder bridges.

5. ALL-WEATHER TECHNICAL BOTTLENECKS ANALYSIS

Based on the above systematic comparisons of experiments and numerics, UHPC strengthening technology has shown good mechanical performance for the rehabilitation of building and bridge structures. However, due to constraints on materials, structure and construction conditions, there are several general technical bottlenecks in the current UHPC retrofitting technology that limit its engineering application (see Fig. 3). They are listed and discussed below.

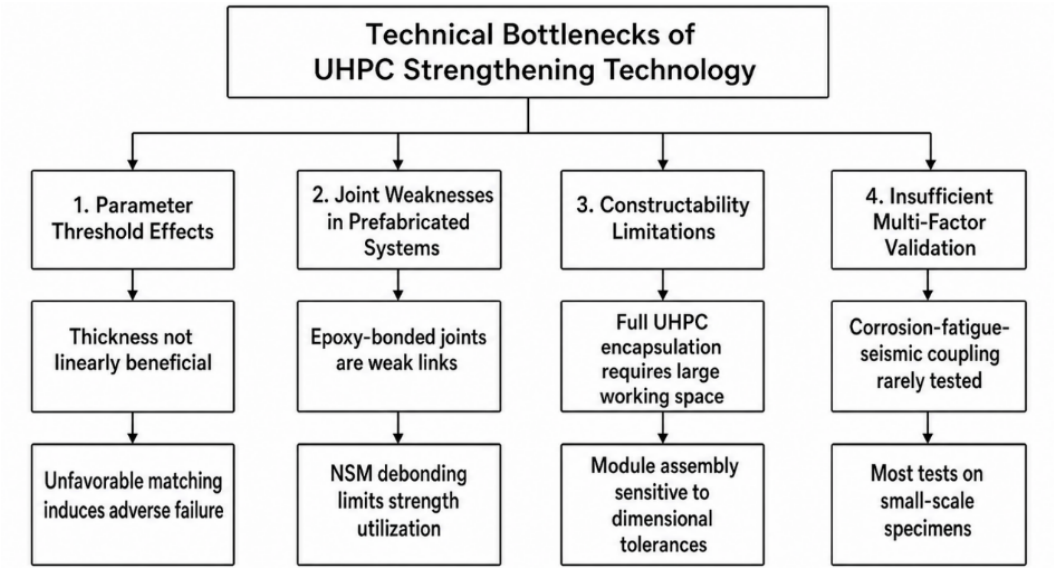


Figure 3. Technical bottlenecks constraining the engineering application of UHPC strengthening technology.

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Threshold effect of parameters and unfavourable matching. Increasing the thickness of the UHPC layer does not continuously improve performance, and if the parameters are not matched properly, adverse failure modes may occur. For instance, too thick UHPC diagonal strips will cause asymmetry in the lateral stiffness of the masonry-infilled frame and lead to out-of-plane buckling [6]. Excessive UHPC overlay thickness in RC beams does not provide additional benefits, so a composite design with fibre reinforcement is required for effective strengthening [1,2]. Based on the above analysis, we believe that a single-parameter optimisation approach will not be feasible.

Inherent Joint Weaknesses in Prefabricated Systems. Prefabricated UHPC strengthening uses off-site production and on-site assembly for module bonding. Epoxy-bonded joints and cast-in-place seams between UHPC components are typical weak links; damage and debonding occur before UHPC matrix failure [4,6]. NSM reinforcement debonding in UHPC-GFRP systems reduces strengthening efficiency further [5]. The above joint defects reduce the general reliability and wider application of prefabricated UHPC strengthening.

Limited Off-Site Constructability. UHPC strengthening has good laboratory performance but is difficult to build in the field. Full UHPC encapsulation requires a large working area, which is not available for in-service bridge beams [2]. Prefabricated module assembly is sensitive to dimensional deviation and installation tolerance, so its actual quality varies. Therefore, they will not be widely used at present.

Lack of multiple-factor coupled experimental verification. Most research uses a single load static test or independent numerical simulation, and there is a lack of data for combined corrosion-fatigue-seismic loading. Real engineering structures are exposed to various factors simultaneously, and single-load tests cannot cover all scenarios. Most of the laboratory tests are conducted on small-scale samples, and the behaviour of full-scale components has not been verified [3,8]. There is no multi-coupling and full-scale data, so the development of high-precision UHPC strengthening design theory is hindered.

6. CONCLUSIONS AND FUTURE OUTLOOK

This paper synthesizes recent experimental and numerical advances in UHPC strengthening technology for typical building and bridge components, examining strengthening mechanisms, performance gains, parameter sensitivities, and engineering applicability, and identifying universal technical bottlenecks. The main conclusions are as follows:

(1) UHPC composite systems outperform conventional retrofitting methods across multiple performance metrics:Fibre-reinforced UHPC overlays can increase the flexural strength and ductility of RC beams; full UHPC encapsulation offers good fatigue repair for bridge T-beams; prefabricated UHPC composites improve column compressive and seismic performance; and UHPC shells and overlays restore seismic and transverse performance of bridge structures.

(2) UHPC strengthening efficiency shows a significant threshold effect. A thicker layer will not necessarily improve performance and may lead to other types of failure. Good Design should optimise the thickness, reinforcement arrangement and structural stress simultaneously.

(3) Prefabricated UHPC systems have inherent weak links:Bonded joints and construction seams of modules are the first failure sites, thus reducing overall reliability. Optimise the system to improve the performance at the joint.

(4) Currently, there are problems of constructability and theoretical support for UHPC strengthening. Space constraints restrict the off-site implementation of some schemes, and due to a lack of multi-factor coupled tests and full-scale verifications, fine-tuned design theories have not been developed.

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To address these bottlenecks, future research should focus on:(1) Multi-factor coupled experiments under corrosion-fatigue-seismic conditions, supplemented by full-scale component validation; (2) high-performance joint materials and integrated assembly methods to address the shortcomings of prefabricated systems; (3) systematic parametric studies to determine optimal Design ranges and standardised guidelines for different component types; and (4) miniaturised, assembled UHPC systems suitable for confined construction spaces, facilitating wider application in engineering.

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