Hybrid Machine Learning and Reliability-Based Models for Predicting the Shear Strength of Synthetic and Steel Fiber-Reinforced Concrete Beams without Stirrups in Construction Sites

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Abstract
Recent advances in machine learning (ML) in construction studies have shown great potential for predicting the shear strength of fiber-reinforced concrete (FRC) beams without stirrups. However, a critical gap remains in addressing uncertainties in material properties and structural parameters, which are vital for reliable structural safety. This study introduces a hybrid framework that integrates ML models—Light Gradient Boosting Machine (LightGBM), Extreme Gradient Boosting (XGBoost), and Gene Expression Programming (GEP)—with reliability-based analysis to predict the shear strength of FRC beams in construction sites. A comprehensive database of 165 experimental beams, including both synthetic fiber reinforced concrete (SyFRC) and steel fiber reinforced concrete (SFRC), was compiled. The findings reveal that LightGBM achieved the highest prediction accuracy with $R^2 = 0.981$. Reliability-based integration improved model robustness, leading to conservative yet accurate predictions. A closed-form reliability-calibrated GEP model is proposed for design use in construction sectors. The study demonstrates that hybrid ML–reliability models offer engineers reliable and precise tools for shear strength prediction for designers in construction projects, with implications for updating construction design codes.

Keywords
Fiber reinforced concrete, Machine learning, Reliability analysis, Beams without stirrups

1. Introduction

Fiber-reinforced concrete (FRC) has become an attractive alternative to conventional reinforced concrete (RC) due to its improved ductility, crack control, and durability. Steel fibers have historically been the most studied, but synthetic fibers such as polypropylene and nylon are increasingly used due to their corrosion resistance and sustainability benefits. Despite these advantages, existing design codes, such as ACI 318-19 and Eurocode 2, provide limited or no provisions for incorporating synthetic fibers in shear strength predictions.

Recent studies have demonstrated that advanced machine learning (ML) models can significantly improve shear strength prediction compared to empirical and regression-based methods. However, most ML studies are deterministic and do not explicitly account for uncertainties in material properties, construction variability, and loading conditions. In structural engineering, where safety is paramount, reliability-based design methods are essential to quantify and manage these uncertainties.

This study addresses these gaps by developing a hybrid framework that integrates ML models with reliability-based methods. The research aims to (i) expand the database of tested FRC beams without stirrups, (ii) evaluate the predictive performance of LightGBM, XGBoost, and GEP, (iii) integrate reliability-based analysis to quantify prediction uncertainty, and (iv) propose a reliability-calibrated closed-form GEP model for practical applications.

The literature only has a few equations predicting the shear strength of fiber-reinforced concrete (FRC) beams without stirrups [5, 9, 10, 13, 19, 23]. Most of these equations were created using regression analysis of tested specimens. Equation (1) should be used to calculate the shear strength (V_c) of RC slender beams lacking shear reinforcement, according to the most recent American Concrete Institute standard (ACI 318-19) [9]. Equation (1) is also applicable for stirrup-free, SFRC slender beams with a steel fiber volume ratio of at least 0.75%.

$$V_C = 0.66\lambda\lambda_s(\rho_w)^{1/3}\sqrt{f'_c}b_w d \quad (1)$$

Where, $\lambda_s = \sqrt{(2/(1+0.004\text{d}))} \leq 1.0$, whilst λ = 1.0 for normal-weight concrete and 0.75 for lightweight concrete, ρ_w is the longitudinal steel reinforcement ratio, f_c' is the concrete compressive strength (MPa), b_w is the beam width (mm), and d is the effective beam depth (mm).

The current study is devoted to helping fill this research gap. The compiled database of tested SyFRC beams without stirrups was assembled, processed, and evaluated to understand the shear performance's key features better. Then, various machine learning algorithms were trained, validated, and tested to assess each algorithm's prediction accuracy and efficiency. Structural engineers are advised to use the most efficient algorithm that satisfies the engineering requirements during the design phase.

2. Materials and Methods

A database of 165 experimental FRC beams without stirrups was compiled from 29 published studies spanning 1992–2023. The database includes 102 SyFRC beams and 63 SFRC beams. Parameters recorded for each specimen include beam width, effective depth, concrete compressive strength, longitudinal steel ratio, fiber volume ratio, and shear span-to-depth ratio.

Three ML algorithms were implemented: Extreme Gradient Boosting (XGBoost), Light Gradient Boosting Machine (LightGBM), and Gene Expression Programming (GEP). The dataset was divided into training (80%) and testing (20%) subsets, with cross-validation ensuring robustness. Hyperparameters were tuned via grid search.

To incorporate uncertainty, Monte Carlo Simulation (MCS) and the First-Order Reliability Method (FORM) were applied. These quantified probability of failure (Pf) and reliability index (β). The hybrid framework combined ML predictions with reliability calibration for conservative yet accurate shear strength estimates.

3. Results and Discussions

Feature importance analysis (via LightGBM) revealed fiber volume ratio (Vf), shear span-to-depth ratio (a/d), and effective depth (d) as the most influential parameters. Beam width, concrete strength, and steel ratio followed.

LightGBM achieved $R^2 = 0.981$, outperforming XGBoost (0.972) and GEP (0.886). The ACI 318-19 equation had the lowest accuracy ($R^2 = 0.742$). Monte Carlo simulations confirmed that variability in Vf and a/d had the greatest effect on shear strength uncertainty. Reliability indices (β) ranged from 2.8 to 4.1, indicating acceptable safety margins.
The reliability-calibrated GEP model is expressed as:

Vn = 0.85 (Vf^0.35)(ρl^0.20)(bw^0.50)(d^0.65)(fc'^0.25)(a/d^-0.45)

This closed-form model balances accuracy with conservatism and is suitable for design practice.

Figure 1 displays the projected shear strength of SyFRC beams without stirrups using *LightGBM*, *XGBoost*, *GEP*, and ACI 318-19; the green dashed line represents the ideal prediction threshold. The solid black line, which represents the best fit line of predictions made using *LightGBM*, is quite near to the green line, indicating high accuracy and data precision.

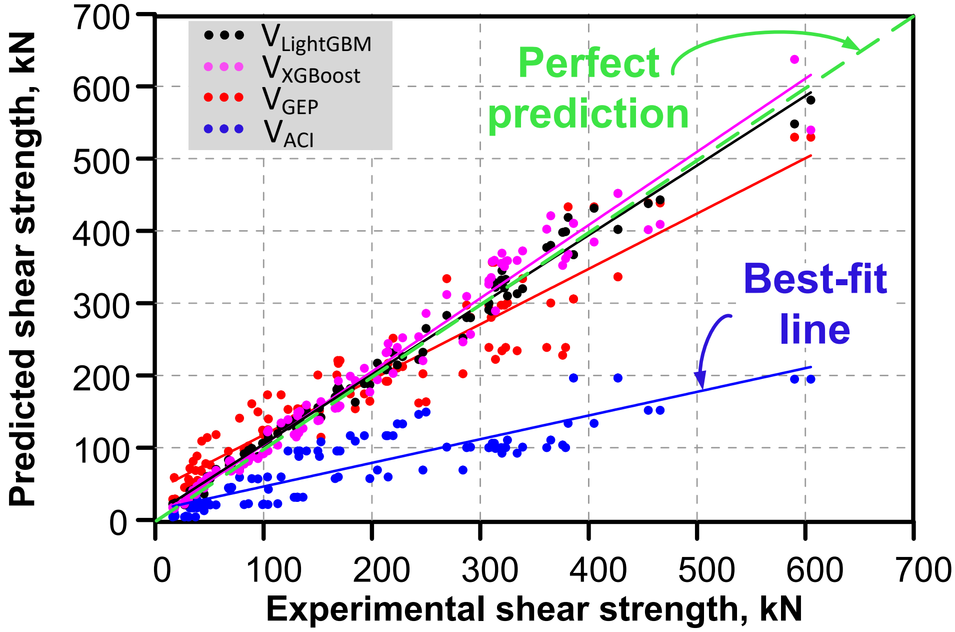

Figure 1. Shear strength prediction of the SyFRC beams reported in the database using $LightGBM$, XGBoost, *GEP*, and ACI 318-19.

The pinkish line, which is the best fit line for the *XGBoost* algorithm's predicted shear strength, is highly similar to the ideal green dashed line. In contrast, the *LightGBM* and *XGBoost* predictions are more precise than the *GEP*-based predictions, and the best fit line (the solid red line) has a little smaller slope than the green dashed line.

As a result, the *GEP* has a propensity to underestimate the shear strength of SyFRC beams without stirrups. The slope of the best fit line (solid blue line) has the lowest slope when compared to the other lines, which means that the ACI 318-19 equation has the least prediction accuracy. The lack of crucial factors for forecasting shear strength, such as the contribution of fibers and shear span-to-depth ratio, is the main reason behind ACI 318-19 equation's deficiencies. Additionally, this equation was created using regression analysis on a small dataset, which limits its ability to estimate the shear strength with the higher required accuracy.

The ACI 318-19 estimates the minimum shear strength of RC beams without stirrups to be at least $^1/_6\, b_w d\sqrt{f_{cm}}$, which reflects the contribution of concrete only and does not consider the contribution of longitudinal steel reinforcement, fibers volume ratio, and beam aspect ratio. Figure 2 (a) shows the effect of the shear span-to-depth ratio on the normalized shear stresses of tested specimens, where the SyFRC deep beams ($a/d \leq 2.5$) have higher values than slender beams ($a/d > 2.5$). This complies with the test results of Altoubat et al. 2009 [11], where the macro synthetic fibers enhanced the arch action in slender beams, resulting in an improvement in shear strength. Deep RC beams with macro synthetic fibers had flexural shear cracking as opposed to the web-shear cracking seen in control RC beams as the mode of failure. Moreover, Parmentier et al. (2012) [29] revealed for a/d between 0.5 and 2.5, the shear capacity was increased by at least 48% when fibers with a volume fraction $V_f = 0.26\%$ were used.

Figure (2 b-d) illustrates that *LightGBM*, XGBoost, and *GEP* predicts the tested SyFRC deep and slender beams very well, with some dispersion of the *GEP* model for SyFRC deep beams. However, Figure (2e) shows the ACI 318-19 predictions do not distinguish between slender and deep beams, with most projections being either less than or equal to $^1/_6\, b_w d\sqrt{f_{cm}}$ as this equation does not consider the a/d parameter. Moreover, the strut-and-tie (STM) model is the most accurate way to predict the load-carrying capacity of deep beams as the arching action increases. The ACI 318-19 code provides the detailed design process for RC deep beams but not SyFRC deep beams. Similarly, Figure (1b-d) shows the normalized shear stresses decrease for beams with high effective depth (d), which confirms the tested results in Figure (1a). This phenomenon is known as the "size effect" which reveals the shear strength of beams is nonproportional to the effective depth. Figure (3e) shows that even though ACI-318-19 contains the size effect factor, $\lambda_s = \sqrt{(2/(1+0.004\text{d}))} \leq 1.0$, that is applicable to RC beams without stirrups. Therefore, the λ_s factor is not suitable for predicting the shear strength of SyFRC beams without stirrups because the predicted shear stresses show no difference in strength between shallow and deep beams.

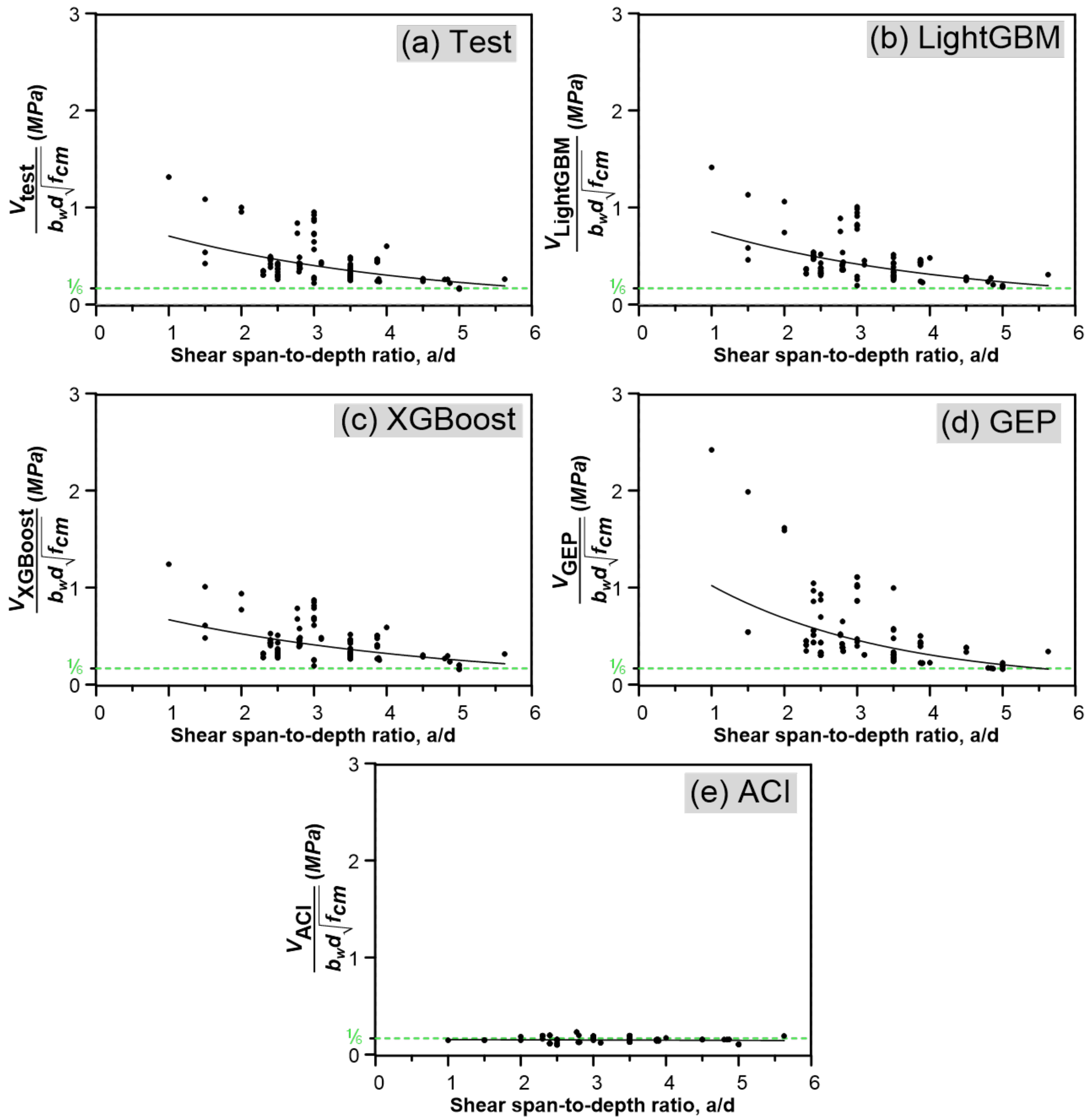

Figure 2. Effect of shear span-to-depth ratio (a/d) on the shear stress of (a) Test results (b) *LightGBM* predictions (c) *XGBoost* predictions (d) *GEP* predictions and (e) ACI 318-19 results.

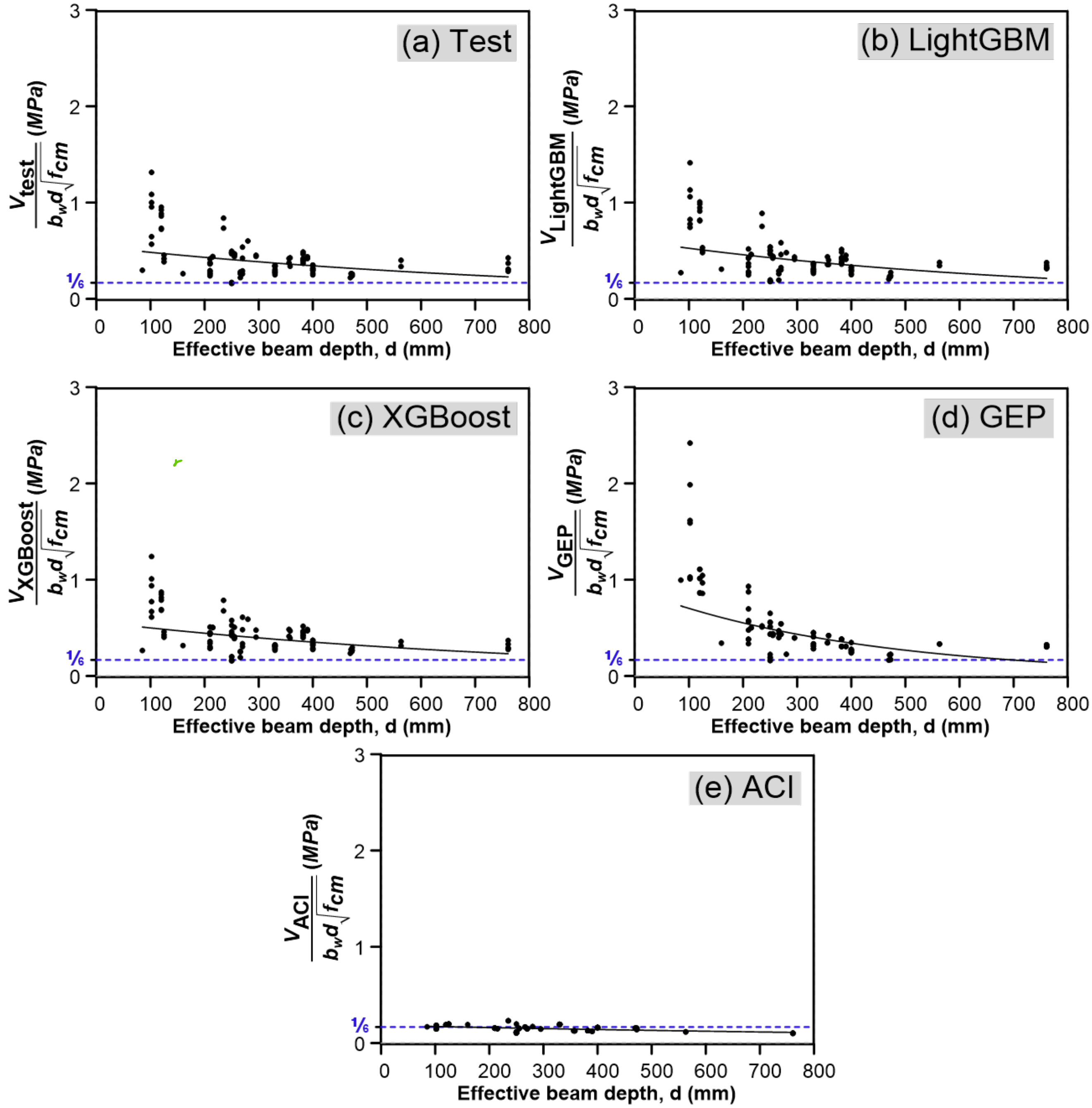

Figure 3. Effect of effective beam depth (d) on the shear stress of (a) Test results, (b) *LightGBM* predictions (c) *XGBoost* predictions (d) *GEP* predictions and (e) ACI 318-19 results (Equation 1).

It is important to note that the created *GEP* model has unique features, such as allowing the user to specify the values for the shear span ratio (*a/d*) and fibers volume ratio (V_f). The results also demonstrate that the model is quite effective compared to the ACI 318-19 code. The current study intends to close a gap in the literature by presenting a comprehensive model that can generate precise shear value estimations. The models now accessible in the literature are not complete regarding the evaluation of shear strefngth. Shear strength evaluation considers several features, including b_w, d, f_{cm} , a/d, $\rho_{w,}$ and V_f, whereas the results of the current study show that V_f and *a/d* are the most significant factors.

The findings confirm that ML models can substantially improve shear strength prediction of FRC beams without stirrups. In particular, LightGBM and XGBoost capture nonlinear relationships between variables, outperforming empirical equations. The integration of reliability analysis enhances confidence in predictions by accounting for uncertainties in materials and geometry.

The proposed GEP model, calibrated for reliability, offers a practical tool for engineers. It explicitly includes fiber volume ratio and shear span-to-depth ratio, which are missing from current design codes. Comparison with ACI 318-19 highlights the limitations of existing provisions, especially for fiber-reinforced beams.

This research suggests that incorporating ML–reliability frameworks into design codes could bridge the gap between academic research and engineering practice, promoting wider adoption of FRC in construction. Subsequent paragraphs, however, are indented (here insert the second paragraph).

5. Conclusions

After analysis and investigation all related factors that effect the shear strength of SyFRC beams without stirrups in construction sites, we conclude some points that listed below:

1. A comprehensive database of 165 FRC beams without stirrups was compiled, including SyFRC and SFRC specimens.
2. LightGBM achieved the highest accuracy ($R^2 = 0.981$), followed by XGBoost (0.972) and GEP (0.886).
3. Feature importance analysis highlighted the critical role of Vf and a/d, parameters absent in design codes.
4. Reliability analysis improved robustness, producing conservative predictions with acceptable safety levels.
5. A closed-form reliability-calibrated GEP model was proposed for practical design use.
6. The hybrid ML–reliability framework provides a strong foundation for future updates of design provisions for FRC beams.

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