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DATA–DRIVEN FINITE ELEMENT MODELLING OF STUB RECYCLED AGGREGATE CONCRETE-FILLED STEEL TUBE COLUMNS

Summary: Concrete-filled steel tubes incorporating recycled aggregate concrete represent a sustainable composite structural members in which the steel tube provides effective confinement and enhances column performance. Although the experimental database for such members has grown in recent years, robust high–fidelity numerical models remain limited. This study presents a computational framework that combines Bayesian optimisation with nonlinear FEM analysis in ABAQUS, automated through MATLAB–Python scripting. The approach optimises key parameters of the confined concrete stress–strain relationship while reproducing experimental axial load–displacement responses of stub columns in compression. The optimised parameters are then used in combination with the regression analysis to develop reliable nonlinear constitutive models for the concrete within steel tube. Additional comparison with two established confined concrete models shows good agreement in load–displacement behaviour and improved performance. The proposed framework is efficient and transferable.

Keywords: concrete-filled steel tube, confined concrete, Bayesian optimisation, composite structure, FEM analysis

MODELIRANJE PODACIMA I KONAČNIM ELEMENTIMA KRATKIH STUBOVA OD ČELIČNIH CEVI ISPUNJENIH BETONOM SA RECIKLIRANIM AGREGATOM

Rezime: Čelične cevi ispunjene betonom sa recikliranim agregatom predstavljaju održiv spregnuti konstruktivni element u kojem čelična cev obezbeđuje efikasno utezanje betona i poboljšava ponašanje stuba. Iako je eksperimentalna baza podataka za ove elemente značajno proširena poslednjih godina, numerički modeli visoke tačnosti i dalje su ograničeni. U radu je predstavljena procedura koja kombinuje Bajesovu optimizaciju i nelinearnu FEM analizu u programu ABAQUS, automatizovanu korišćenjem MATLAB–Python skripti. Pristup omogućava optimizaciju ključnih parametara konstitutivnog modela utegnutog betona uz vernu reprodukciju eksperimentalnih dijagrama aksijalna sila–pomeranje kratkih stubova pri pritisku. Optimizovani parametri su zatim korišćeni u kombinaciji sa regresionom analizom za razvoj pouzdanog nelinearnog konstitutivnog modela betona utegnutog čeličnom cevi. Dodatno poređenje i dva poznata modela utegnutog betona pokazuje dobro slaganje u pogledu ponašanja sila–pomeranje i poboljšanu tačnost. Predloženi pristup je efikasan i široko primenljiv.

Ključne reči: čelična cev ispunjena betonom, utegnut beton, Bajesova optimizacija, spregnuta konstrukcija, metod konačnih elemenata

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1. INTRODUCTION

The growing emphasis on sustainable construction has stimulated extensive research into recycled aggregate concrete-filled steel tube (RACFST) columns as an environmentally responsible alternative to conventional composite members [1]. In these structural elements, recycled aggregate concrete (RAC) is confined by the surrounding steel tube, which improves its strength, ductility and overall structural performance. Despite the generally lower mechanical properties of RAC compared with natural aggregate concrete (NAC), experimental studies have demonstrated that appropriate confinement can effectively compensate for these deficiencies [2, 3].

The structural response of RACFST columns is governed by complex interactions between the steel tube and the confined concrete core. Existing numerical approaches commonly rely on stress–strain relationships originally developed for confined NAC and subsequently modified for recycled aggregate concrete. However, many of these models are calibrated using limited experimental datasets, which restricts their applicability across a broader range of material and geometric parameters. Furthermore, current European design provisions for composite structures do not provide specific guidance for RACFST members [4].

Recent developments in data-driven structural modelling demonstrate that integrating experimental databases with optimisation algorithms and numerical simulations can significantly enhance predictive capability [5, 6]. Motivated by these findings, this study presents an automated framework that integrates Bayesian optimisation in MATLAB with nonlinear finite element simulations in ABAQUS for the modelling of axially loaded stub RACFST columns. The concrete constitutive model is calibrated using an extensive experimental database, enabling systematic identification of key parameters governing the behaviour of confined RAC. Particular attention is given to the prediction of complete axial load–displacement responses and ultimate column resistance. The optimised parameters are subsequently used to establish regression-based relationships suitable for practical implementation. Further details regarding the 3D model parameters and concrete constitutive model development can be found in the authors' recent publication by Nikolić *et al.* [7].

The primary focus of this paper is the comparative assessment of the Proposed model against the confined concrete models developed by Tao *et al.* [8] and Han *et al.* [9], which are widely used for the analysis of RACFST columns and have not previously been validated against a large experimental database. A secondary objective is to present the proposed computational framework and its methodological workflow, highlighting the transferability and applicability of the developed approach to similar structural modelling problems. The predictive performance of the methodology has been previously validated against experimental results, confirming its capability to accurately reproduce both the axial load–displacement response and ultimate resistance of RACFST columns [7].

2. EXPERIMENTAL DATABASE

As a first step, existing experimental studies on RACFST stub columns were reviewed and relevant data were extracted to develop a unified database. In total, 18 SCIE-indexed studies published between 2006 and 2025 were examined, and only circular stub columns with a length-to-diameter ratio $(L/D)\leq 5.0$ using carbon steel tubes were retained for consistency. After screening and harmonising the reported geometric, a final database comprising 209 specimens was compiled. Distribution of the key geometric and material parameters in the RACFST database, including diameter-to-thickness ratio (D/t), cylinder compressive strength (f'_c), replacement ratio (r) and steel yield strength (f_y), is presented in Figure 1.

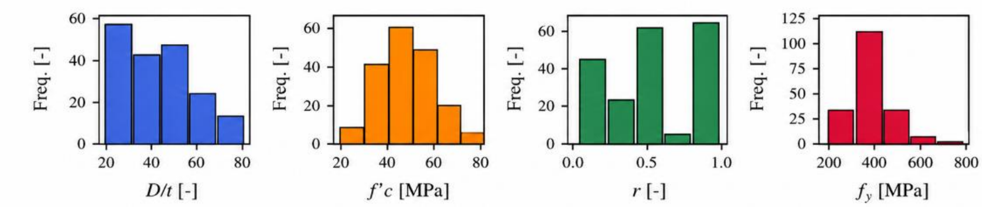

Figure 1: Distribution of key geometric and material parameters in the RACFST database

3. AUTOMATED MODELLING FRAMEWORK

The overall workflow presented in this study is illustrated in Figure 2. The proposed framework combines an experimental database, finite element simulations and Bayesian optimisation within an automated MATLAB–Python–ABAQUS environment. The workflow enables systematic calibration of key constitutive parameters, development of regression-based relationships and subsequent validation against experimental results.

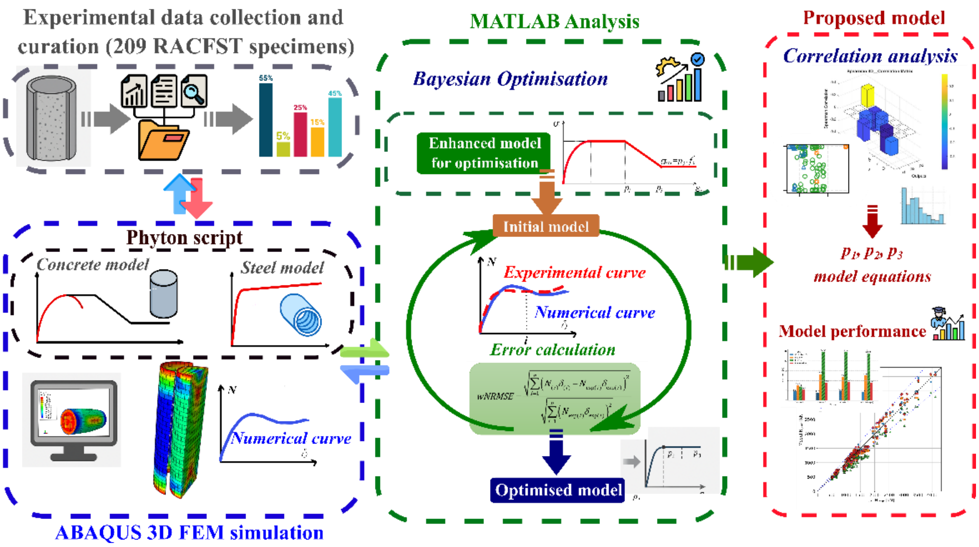

Figure 2: Workflow of the proposed data-driven framework from Nikolić et al. [7]

3.1. FINITE ELEMENT MODEL (FEM)

The FEM of the RACFST specimen was developed in ABAQUS using 8-node reduced-integration brick elements (C3D8R) for both the steel tube and concrete core. Boundary conditions were applied through reference points located at the centres of the top and bottom faces, with all nodes on the corresponding surfaces coupled to these points. Specimens were subjected to displacement-controlled axial loading, consistent with standard experimental testing procedures. The numerical model required geometric inputs including column diameter, steel tube thickness and column length (*D, t, L*), together with the material properties defined through the constitutive models described in the following sections.

3.2. STEEL CONSTITUTIVE MODEL

Several constitutive models have been proposed in the literature to represent the behaviour of carbon steel, ranging from elastic–perfectly plastic to bilinear and multilinear formulations. Preliminary analyses performed in this study indicated that the inclusion of strain hardening improves the prediction of the peak resistance of RACFST columns. Consequently, the two-stage Ramberg–Osgood model for cold-formed steel recommended in the second-generation Eurocode 3 Part 1-14 [10] was adopted for all numerical simulations.

3.3. CONFINED RAC MODEL FOR OPTIMISATION

In Eurocode-based nonlinear analysis, the Eurocode 2 (EC2) concrete model [11] is insufficient for representing the enhanced ductility of confined concrete in composite columns. To capture the post-peak behaviour observed in RACFST members, an extended constitutive formulation was adopted for the calibration procedure.

The Enhanced model for optimisation shown in Figure 3 (red line) is based on the EC2 formulation and incorporates modifications inspired by the work of Portolés *et al.* [12]. The model consists of an EC2 ascending branch, a ductility plateau, a linear softening branch and a residual stress plateau. Three parameters (p_1, p_2 and p_3) are set to govern the confined concrete post-peak response and were selected as optimisation variables within the Bayesian calibration framework. For comparison purposes, an Extended EC2 model was also considered by extending the standard EC2 curve beyond its 3.5‰ strain limit until the stress reduced to 10% of cylinder compressive strength $f_c^{'}$, followed by a horizontal plastic branch.

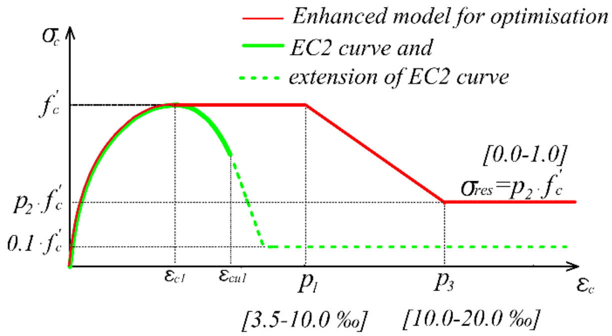

Figure 3: Enhanced model for optimisation vs Extended EC2 model

4. BAYESIAN OPTIMISATION PROCEDURE

4.1. OPTIMISATION FRAMEWORK

Given the large number of specimens and the nonlinear nature of the calibration problem, Bayesian optimisation was employed to efficiently identify the optimal values of the three constitutive parameters (p_1, p_2 and p_3) within their assumed ranges, defining the Enhanced concrete model for optimisation. The optimisation procedure was implemented using the *bayesopt* routine in MATLAB and integrated with the automated ABAQUS simulation framework described previously. Since the objective of the study was to reproduce the complete axial load–displacement response (N–δ) rather than only the ultimate resistance, an error metric capable of evaluating the entire response curve was required. The objective function was defined as weighted normalised root-mean-square error (wNRMSE) based on the axial energy response. For each specimen, Bayesian optimisation iteratively updated the parameter values based on the observed prediction error, repeating finite element simulations by minimising the discrepancy between the experimental and numerical load–displacement responses. The resulting optimised parameters were subsequently used to establish regression–based constitutive relationships suitable for practical implementation.

4.2. STATISTICAL ANALYSIS AND DEVELOPMENT OF REGRESSION RELATIONSHIPS

The optimised parameter values for 209 specimen dataset obtained from Bayesian optimisation were subsequently analysed to identify trends and relationships with the governing geometric and material properties. Following a data screening procedure to address inconsistencies in the experimental records, the initial dataset was refined to a final calibration database of 150 specimens. Statistical distributions and correlation analyses between specimen input variables and parameters were performed as in Figure 4. The results showed that p_1 and p_3 exhibit relatively compact distributions, whereas p_2 demonstrates substantially greater variability and stronger sensitivity to confinement-related parameters. Additionally, correlation analysis indicated that no single variable dominates the behaviour of the calibrated parameters, supporting the use of multivariate nonlinear regression techniques.

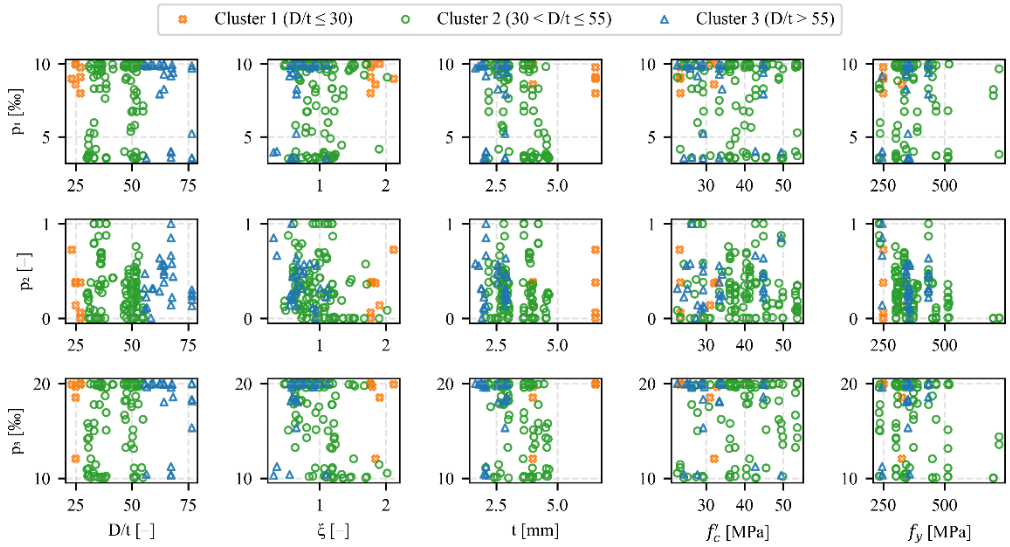

Figure 4: Scatter plots of input variables vs. model params (p_1, p_2, p_3), per cluster from [7]

4.3. CLUSTER-BASED REGRESSION STRATEGY

To improve predictive capability and account for different confinement levels, the dataset was further partitioned according to the diameter-to-thickness ratio (*D/t*). This ratio was selected as the clustering variable because of its clear physical significance. It directly reflects the sectional slenderness of the steel tube and strongly influences the confinement level and deformation capacity of the concrete core. Three confinement-based clusters were defined: Cluster 1 ($D/t < 30$), Cluster 2 ($30 \leq D/t \leq 55$), and Cluster 3 ($D/t > 55$), representing strong, intermediate and weak confinement, respectively. Further on, separate regression models were subsequently developed for parameters in each cluster. The resulting regression equations and their development are presented in detail in Nikolić *et al.* [7].

5. COMPARATIVE ASSESSMENT WITH OTHER MODELS

The predictive capability of the Proposed model was previously validated against the complete experimental axial load–displacement (N–δ) responses of the 150-specimen calibration database presented in [7] and against RACFST column response with the utilised EC extended model.

In this paper, the Proposed model is further assessed through comparison with two well-established confined concrete models by Tao *et al.* [8] and the model proposed by Han *et al.* [9], later adapted for RACFST columns by Lyu *et al.* [13]. The Tao model represents confined concrete behaviour using a three-stage stress–strain relationship consisting of an initial ascending branch based on unconfined concrete, a plateau region accounting for the increased peak strain due to confinement, and a post-peak softening branch with enhanced ductility provided by the steel tube confinement. The Han model accounts for the passive confinement provided by the steel tube by increasing both the peak strain and the post-peak ductility of the concrete, with the extent of these enhancements governed by the confinement factor. To account for the higher peak strain of RAC, the original formulation was modified in the study by Lyu *et al.* [13] using the peak strain expression for RAC. Figure 5a illustrates the constitutive stress–strain relationships obtained using the EC2 extended, Proposed, Tao and Han models for a representative RACFST specimen (C140-50-1) reported in [13].

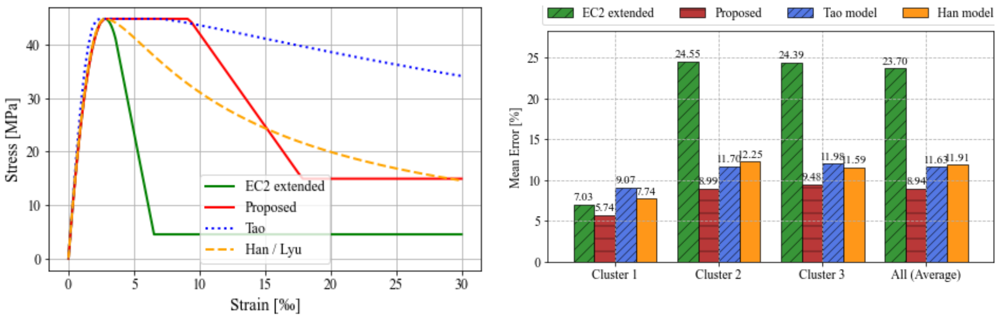

Figure 5: a) Comparison of confined concrete models on specimen C140-50-1 from [13], b) Average wNRMSE of each model per cluster and overall

Figure 5b shows that the Proposed model achieves the lowest average error compared to specimen tests (8.94%), indicating its strong predictive capability for practical applications and significantly outperforming the Extended EC2 model (23.70%). Compared with the established confined concrete models of Tao (11.63%) and Han (11.91%), the Proposed model also demonstrates improved predictive performance. This is particularly noteworthy given that these widely adopted models have not previously been evaluated against a large RACFST experimental database [1]. Furthermore, the Proposed model exhibits more consistent performance across all clusters, indicating a better representation of confinement effects and the nonlinear interaction between steel and recycled aggregate concrete as a function of the *D/t* ratio.

Representative specimens covering different confinement levels are presented in Figure 6 to illustrate the ability of the proposed model to accurately reproduce the complete N–δ response. In addition, the mean prediction error and standard deviation of the ultimate axial resistance reported in Table 1 further confirm the improved accuracy and consistency of the proposed model across different confinement levels when compared to other considered models.

Table 1: Mean wMNRSE error ± standard deviation of whole axial resistance in [%]

Cluster	EC2 extended	Proposed	Tao model	Han model
Cluster 1	7.03 ± 2.76	5.74 ± 2.4	9.07 ± 5.27	7.74 ± 3.4
Cluster 2	24.55 ± 56.95	8.99 ± 5.33	11.7 ± 7.01	12.25 ± 7.59
Cluster 3	24.39 ± 12.7	9.48 ± 4.96	11.98 ± 8.22	11.59 ± 7.05
All (Average)	23.7 ± 50.04	8.94 ± 5.19	11.63 ± 7.17	11.91 ± 7.38

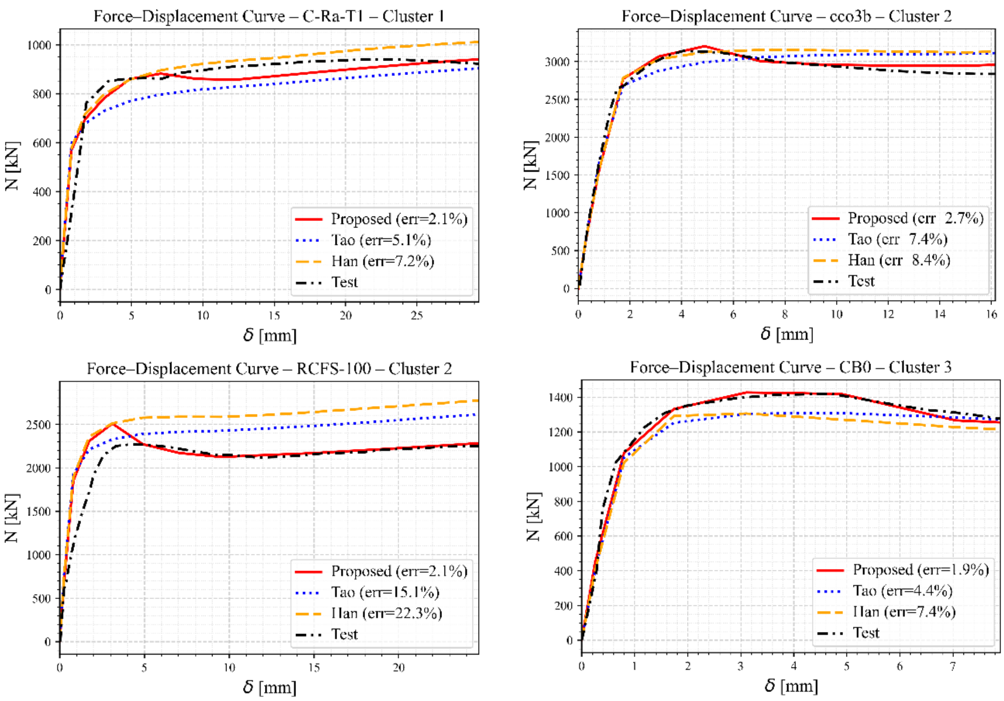

Figure 6: N–δ curves comparison for representative specimens covering different clusters

6. CONCLUSION

This paper briefly presented the computational workflow previously developed for the calibration of confined concrete constitutive models for application in finite element modelling of RACFST columns. The workflow provides a systematic and transferable methodology for integrating experimental data, finite element simulations, and Bayesian optimisation in the calibration of constitutive model parameters. The applicability of the proposed model was further assessed through comparison with two widely adopted confined concrete models proposed by Tao and Han. Among the investigated models, the proposed model achieved the lowest average prediction error and the most consistent performance across the considered confinement levels. Benchmarking against the Tao and Han models demonstrated improved predictive accuracy, particularly for specimens with higher confinement levels, indicating a more accurate representation of the interaction between steel confinement and recycled aggregate concrete. The presented results further support the applicability of the proposed model for the analysis of RACFST columns and encourage the broader adoption of sustainable structural solutions based on recycled aggregate concrete.

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