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1. Introduction

This repository contains files supporting a machine learning-integrated finite element modeling framework for reinforced concrete (RC) structural walls.

The finite element model, developed within the OpenSees software framework, simulates the behavior of structural walls under quasi-static cyclic loads. It is a macroscopic two-dimensional fiber beam-column model with a displacement-based formulation that accounts for several mechanisms influencing the hysteretic behavior, strength degradation and failure of RC structural walls, including bar rupture and buckling, low-cycle fatigue effects, shear, and anchorage deformations.

The strain localization issues for walls with softening moment-curvature response are addressed by setting the base element length equal to two times the estimated plastic hinge length of the wall and employing the Gauss-Legendre integration technique with two integration points per element. The proposed finite element model is particularly efficient in estimating the displacement capacity and strength degradation of ductile (i.e., flexure and flexure-shear controlled) rectangular and barbell walls, with the best results expected for specimens with large axial loads (i.e., axial load ratio about 20% or larger). The FE model should not be used, however, to study flanged (i.e., I, L, T, and U-shaped) ductile walls or squat shear-controlled specimens.

The finite element model was calibrated over 140 experimental specimens, summarized in the `DeltaU_Database.xlsx` spreadsheet. The proposed macro model can be studied using the accompanying example (i.e., `WSH6_Model01.tcl`) available in the present repository.

The finite element model uses the modified peak strain of concrete as its calibration parameter. To make the FE modeling approach applicable to untested specimens, two Simple Weighted Ensemble machine learning models were developed in MATLAB. These ML models can estimate the calibration parameter (i.e., the modified peak concrete strain) of structural walls based on their geometrical, mechanical, and loading properties. The first Ensemble model was trained, validated, and tested on the full 140-unit database, while the second model employed a subset of 110 specimens with boundary elements. The training, validation, and testing process was repeated 10 times for each category of walls. The two Ensemble models with the best results on their hold-out testing data are selected for evaluating the peak concrete strain of new specimens. Both Ensemble models are archived in the `MLmodel.zip` file.

To use these Ensemble models for estimating the peak concrete strain of their hold-out test specimens, as well as any new specimen, a MATLAB script (`peakStrainEstimator01.m`) is included in the `MLmodel.zip` archive file. `peakStrainEstimator01.m` script utilizes pre-trained ML models (`chosen.mat` files) and their assigned weights to predict the modified peak strain of concrete for a given specimen. The zip file also includes support files and functions to execute `peakStrainEstimator01.m`.

`peakStrainEstimator01.m` reads the input parameter (feature) information for hold-out test specimens of either category from the `Features.csv` files. Input parameters of new specimens can be introduced to the ML model in the same way to predict the calibration parameters for the FE modeling. The 140-unit Ensemble model must be used for specimens WITHOUT boundary elements. For walls WITH boundary elements, either 140- or 110-unit Ensemble models can be utilized. Nonetheless, it was observed during the training process that the 110-unit model generally yields smaller estimation errors.

Additional information about the contents of the present repository is provided in the following sections.

2. The Assembled Database for the ML-Integrated FE Model

`DeltaU_Database.xlsx` An Excel spreadsheet that includes the database used to train, validate, and test the Simple Weighted Ensemble machine learning models for predicting the modified peak strain of concrete. It also includes hyperparameter information for ML model reproducibility. DeltaU_Database.xlsx consists of four sheets:

i. Bibliographic references for the assembled data;
ii. Specimen names, features and outputs (i.e., the optimum peak concrete strain values) for the 140-unit category of experimental specimens;
iii. Specimen names, features and outputs for the 110-unit category of experimental specimens, which are walls with boundary elements;
iv. List of hyperparameters and their optimum values for training individual ML models.

3. The Finite Element Model Example and the Auxiliary Files

`WSH6_Model01.tcl` The finite element model of specimen WSH6 (Dazio et al. (2009)) has been provided as an example of the developed modeling approach for ductile RC structural walls.

The FE-model script is written in the Tcl programming language and can be executed in the OpenSees framework. Apart from introducing the appropriate path for the output files directory by modifying the `resultsDir` variable, no other adjustment is required to run the model, provided that OpenSees has been set up.

`WSH6_measured.csv` A csv file including the measured lateral load-displacement information of the experimental specimen WSH6. The data by this file allows for comparison between the measured values by (Dazio et al. (2009)) and the analysis results by `WSH6_Model01.tcl` model.

`sectionCoordinateGuide.pdf` A visual guide to the element local axes and locations of the generated auxiliary points by `WSH6_Model01.tcl` for defining the concrete fibers.

4. MATLAB Script, Functions, Pre-trained Models, and the Supporting Files

`MLmodel.zip` contains pre-trained single ML models, information about the weights assigned to the single models of the two Ensemble models, hold-out specimen data, and supporting files for estimating the peak concrete strain of the hold-out specimens or any new wall. To be more accurate, `MLmodel.zip` includes a MATLAB script (i.e., `peakStrainEstimator01.m`) and three folders.

As mentioned earlier, `peakStrainEstimator01.m` predicts the peak concrete strain values of the hold-out specimens in either the 140- or 110-unit category based on their input parameters and prints the estimated results on screen. Once executed, the script displays a prompt message asking the user whether the 140- or 110-unit category Ensemble Model must be employed. The user is expected to enter `140` for the 140-unit and `110` for the 110-unit category. Assuming that the files and folders in `MLmodel.zip` are stored with the default order on the local hard disk, no additional adjustment is required for `peakStrainEstimator01.m` by the user. `peakStrainEstimator01.m` is developed in MATLAB R2022b environment.

The included 3 folders are as follows:

i. `codeFunctions` folder contains functions required by `peakStrainEstimator01.m`. Apart from `backTransform.m` and `MyscaleData.m`, all other functions in the `codeFunctions` subdirectory are developed by (Camps-Valls et al, 2016).
ii. `140-Walls` folder contains 1 CSV file (`Features.csv`) and 3 subdirectories. `Features.csv` lists information about the names and input parameters of the hold-out specimens of the 140-unit category. Properties of new specimens can be introduced to the ML model in a similar manner. Two subdirectories (i.e., `KRR` and `SVR`) each contain a pre-trained single ML model (`chosen.mat`) and its optimum weight (`weight.txt`) determined during the model training-validation process. These files are automatically utilized by the `peakStrainEstimator01.m` script and need no modifications. The third subdirectory, `supportFiles`, contains data for model output decentering (`meanY.txt`) and feature scaling (`XtrainMin.txt` & `XtrainMax.txt`), as the

single ML models were trained on centered outputs and scaled features. No modifications are required for these files as well.

iii. `110-Walls` folder is similar to the `140-Walls` folder, except that it has 4 subdirectories, including the single ML model subdirectories (i.e., `KRR`, `SVR` and `GPR`), and the `supportFiles` subdirectory. Moreover, the usage of the `110-Walls` folder is restricted to structural walls with boundary elements.

It is observed that the 140-unit category Ensemble Model uses two pre-trained single ML models (i.e., KRR- and SVR-based), while the 110-unit category Ensemble Model uses three pre-trained single ML models (i.e., GPR-, KRR- and SVR-based). Weight values assigned to the single ML models by the two Ensemble Models are as follows:

- 140-unit category Ensemble Model: KRR(1.0) and SVR(0.9)
- 110-unit category Ensemble Model: GPR(1.0), KRR (1.0) and SVR(1.0)

5. Important Notes and Reminders

To execute `WSH6_Model01.tcl`, specify the appropriate path to the output files directory by modifying the `resultsDir` variable.

i. After unzipping, it is recommended to retain the order/arrangement of the files and folders of `MLmodel.zip` as the default on the local hard disk. Otherwise, issues may arise while executing `peakStrainEstimator01.m`.

ii. If MATLAB encounters problems recompiling the MEX files in the `codeFunctions` (e.g., `mysvmpredict.mexw64`), the user is recommended to consider installing the simpleR toolbox (Camps-Valls et al, 2016).[1]

iv. To estimate the modified peak concrete strain for a new specimen WITHOUT boundary elements, its features are added to the `Features.csv` file in the 140-Walls directory, `peakStrainEstimator01.m` is executed, and `140` is entered when the prompt message appears. For specimens WITH boundary elements, either the 140- or 110-unit category Ensemble model may be utilized by entering `140` or `110`, respectively, when the prompt message is displayed.

v. `peakStrainEstimator01.m` has been tested only on Windows 10/11 and macOS (Apple Silicon M2) platforms, using MATLAB 2017b and 2022b. Nonetheless, the code has not been tested using older MATLAB versions or

[1] https://github.com/IPL-UV/simpleR

other operating systems (e.g., Linux, ChromeOS, etc.) Feedback on untested operating systems and MATLAB versions is appreciated.

6. References

Camps-Valls, G., Gómez-Chova, L., Muñoz-Marí, J., Lázaro-Gredilla, M., & Verrelst, J. (2016, 3). simpleR: A simple educational Matlab toolbox for statistical regression (Version 3.0). Retrieved from http://www.uv.es/gcamps/

Dazio, A., Beyer, K., & Bachmann, H. (2009). Quasi-static cyclic tests and plastic hinge analysis of RC structural walls. *Engineering Structures, 31(7)*, 1556–1571.

7. Contact Information

For questions, bug reports, or suggestions regarding this repository, please contact:

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Appendix i) Expected Values for Peak Concrete Strain Predictions

The following results must appear on screen with the current settings after `peakStrainEstimator01.m` is executed.

For the 140-unit category:

Specimens	Ensemble	KRR_single	SVR_single
SW7	0.010970	0.010785	0.011175
FW4	0.001523	0.001367	0.001697
W6	0.001773	0.001708	0.001846
SOLID	0.004045	0.004277	0.003786
WSH4	0.002192	0.002475	0.001877
W4	0.007882	0.007360	0.008463
SW1	0.003624	0.003804	0.003424
HW-1	0.006274	0.006813	0.005676
Slender Wall	0.003817	0.003809	0.003825
W2	0.013372	0.012305	0.014556

For the 110-unit category:

Specimens	Ensemble	KRR_single	SVR_single	GPR_single
NW-1	0.0035729	0.0045822	0.0034583	0.0026782
WSH6	0.0032224	0.0036875	0.0029293	0.0030505
H10	0.0026617	0.0026255	0.0028856	0.0024741
SW33	0.0030161	0.0029947	0.0031011	0.0029524
SW9	0.0143131	0.0156168	0.0114291	0.0158935
W11	0.0024276	0.0024548	0.0026512	0.0021767
MW	0.0029174	0.0030236	0.0029990	0.0027295
SWY1	0.0055239	0.0055804	0.0053468	0.0056447
SW-0.45	0.0071074	0.0079138	0.0075848	0.0058236
WR-20	0.0031888	0.0032357	0.0033063	0.0030244