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Modeling nonlinear behavior of Buckling-Restrained Braces via different artificial intelligence methods

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ABSTRACT

Five AI models are presented to model the dynamic nonlinear behavior of Buckling-Restrained Braces (BRBs). The AI techniques utilized in the models are: Time-Delayed Neural Networks (TDNN), Nonlinear Auto-Regressive eXogenous (NARX) neural networks, Gaussian-Mixture Models Regression (GMMR), Adaptive Neuro-Fuzzy Inference Systems (ANFIS) and Polynomial Classifier Regression (PCR). The models are developed using time-delayed brace displacements inputs and brace force outputs to predict updated brace forces during load reversals. The training and testing of the AI models are performed using experimental data from BRB specimens tested at the Pacific Earthquake Engineering Research (PEER) Center. The training stage for every method makes use of the experimental data from one specimen. In order to assess the models' learning and generalization capabilities, three sets of experimental data for different specimens are used. To arrive at an optimized architecture that best models the phenomenon, the model performance with different parameters is evaluated. The brace force predicted by the proposed model shows excellent resemblance to the experimental results for the training sample, for all techniques. The predicted behavior of the testing samples shows noticeable accuracy and further demonstrates the generalization and prediction capability of the proposed modeling techniques. The various techniques are compared on the basis of selected performance criteria. It is found that the performance of two AI techniques standout among the others: the NARX and the PCR. Although the NARX demonstrates a slight advantage in the prediction accuracy over the PCR, the latter is far more superior in terms of computational efficiency. Thus, the PCR would be recommended for scenarios where online training is needed. The BRB design and performance investigation processes can be facilitated by the developed modeling techniques thus minimizing the need for, and extent of, experimental testing.

1. Introduction and background

As far as nonlinear behavior is concerned, conventional concentric braces are prone to many drawbacks. Low ductility, asymmetrical behavior (hysteretic curves) in tension versus compression, strength deterioration and stiffness degradation are quite common to conventional braces [1]. Such poor performance under load reversals opens the gateway for research to develop improved alternatives. A reliable solution, to most if not all the limitations of conventional braces, is offered by Buckling-Restrained Braces (BRBs). The qualitative improvement of BRBs to conventional braces' hysteretic behavior (cyclic force–displacement relationship) is depicted in Fig. 1. The BRB's structure comprises of a low-yield steel core embedding into an outer casing of concrete-filled steel tube. This surrounding encasement eliminates the global buckling of the steel core and allows it to withstand significant levels of inelastic deformations. BRBs are associated with stable hysteretic behavior and exhibit superb energy dissipation capabilities. Fig. 2 [2] illustrates the anatomy of a typical BRB. In the last decade or so several experimental studies have been conducted for BRBs components as well as assemblages (e.g.: [2–8]). Other numerical investigations have also been recently conducted (e.g.: [9,10]).

It is observed that there exists a significant difference between the BRB tension and compression capacities despite the stable hysteretic behavior exhibited by BRBs under load reversals. Due to the decoupled confinement of the brace, geometric nonlinearity like isotropic hardening is also introduced. In order to minimize the cost of experimental results, cost effective and highly refined

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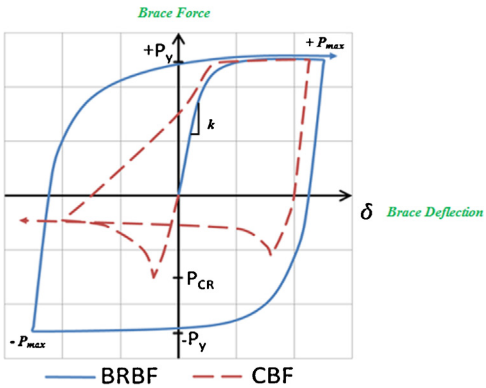

Fig. 1. Comparison of behaviors between BRBF and CBF.
Adopted from Starseismic (2012).

modeling techniques encompassing BRB peculiar dynamic nonlinear behavior are motivated. Finite Element Analysis (FEA) has served as an excellent and validated substitute to extensive experimental programs. However, when compared to the experimental efforts, explicit FEA modeling is not a trivial task either and significant efforts remain needed. Moreover, similar to physical experiments, the FEA lacks the capability of producing closed-form solutions to the simulations. Hence, the need for general modeling techniques continues to exist, and therefore, artificial intelligence (AI) is explored in this research.

The problem at hand can be viewed as a black-box system identification problem whereby an AI model is determined based on a learning scheme operating on experimental measurements. These measurements represent input and output data obtained from the actual system as will be described in the experimental data section (Section 2). The selection of an AI model is based on its suitability to capture the time variant nonlinear dynamics of the system to be modeled. Accordingly, in this paper we examine five AI models configured in a way such that they are able to capture the time variant nonlinear dynamics of the BRB system. Capturing nonlinearity and time variance is achieved by using multilayer architecture, nonlinear activation functions, and time delays in the AI models.

The AI techniques investigated in this paper are: (a) Time-Delayed Neural Networks (TDNN), (b) Nonlinear Auto-Regressive eXogenous (NARX) neural networks, (c) Gaussian Mixture Models Regression (GMMR), (d) Adaptive Neuro-Fuzzy Inference System (ANFIS) based regression and (e) Polynomial classifiers based regression (PCR).

The following organization is adopted in this paper: Section 2 describes the experimental data utilized for training and testing the different intelligent techniques used in this paper. Predicted brace force results using the five AI techniques are illustrated in Sections 3–6 along with descriptions of the corresponding techniques except for the NARX method. The reader is referred to our previously published work in [11] which provides detailed description of the NARX method. The relevant results of the NARX method are re-presented in this paper for the sake of comparison and completeness. Section 3 focuses on TDNN and NARX, Section 4 focuses on GMMR, Section 5 focuses on ANFIS, and Section 6 focuses on PCR. Comparison of the performance of the different modeling techniques is presented and discussed in Section 7. Finally, the paper is concluded in Section 8.

2. Experimental data

The experimental data utilized to develop the different intelligent models were those of the full-scale tests performed by Uriz and Mahin [8] at the University of California at Berkley.

2.1. BRB specimens

Four BRB specimens representative of modern code-compliant construction, fabricated at or near full scale were selected for full scale testing. The testing setup comprised of two stories, realistic boundary conditions, and BRBs were subjected to load reversals resembling intense earthquake ground motions. Specifically, three one-bay wide, two-story planar frames were tested. The upper stories were stiffened and strengthened for these specimens so that inelastic deformations would be concentrated in the lower stories containing the BRBs. Intense shaking was applied to both inverted V and single diagonal braced frames configurations (Fig. 3a and b, respectively). In this study, specimen BRB-3 test results are used for training the network. The test results from the remainder of the specimens are utilized for testing the network's prediction capability.

2.2. Experimental testing protocol

The conducted experiments followed the standard loading protocol provisions outlined in the AISC/SEAOC Recommended Buckling-Restrained Brace Frame Provisions [12]. The protocol comprises of 16 cycles and is designed to demonstrate the desirable stable hysteretic behavior by subjecting the specimen to sufficient accumulated inelastic demands. Fig. 4 provides a graphical representation of the loading protocol. Details of the four specimens are listed in Table 1. Further description of the experimental program and the specimens can be found in the PEER report no. 2008/08 [8].

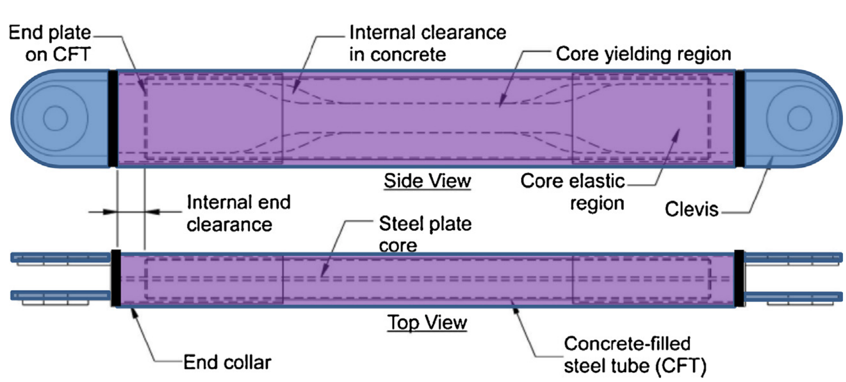

Fig. 2. BRB schematic.
Adopted from [2].