Challenges in Determining Nonlinear Modeling Parameters of FRP-Retrofitted Shear Walls

J. Dukes and S. Sattar

ABSTRACT

Fiber reinforced polymer (FRP) has become more prevalent and accepted as a construction material, and particularly as a retrofit technique. However, there remains a need for design guides and standards for FRP-retrofitted components and structures, including nonlinear modeling parameters that guide the design and analysis of components in PBSD codes such as ASCE 41 and ACI 369. As part of ongoing research of developing modeling parameters for FRP-retrofitted shear walls, the authors needed to identify FRP material properties that influence component nonlinear response. However, the reporting of FRP material properties has not been consistent in prior experimental programs. For example, a report describing an experiment of an FRP-retrofitted component would include either fiber material properties or composite material properties, but not both. Two options were explored to address the in consistency in FRP material property reporting: using only data with composite properties or converting fiber properties with a rule-of-mixtures approximation. The results of a regression analysis show that the regression model with the composite-only data performed better than the model with converted properties. These results will inform the development of modeling parameters of FRP-retrofitted walls and inform the need to establish better data collection processes for FRP material properties.

Introduction

Fiber reinforced polymer (FRP) composites have become a widely used and researched material in the civil and structural engineering fields. FRP composites have many advantages as a construction material, such as being corrosion resistant, lightweight and relatively easy to install. Externally bonded FRP has become a popular retrofit and strengthening technique used to improve the performance of reinforced concrete components such as columns, beams, and shear walls. However, there are critical research gaps regarding the initial and long term performance of FRP materials and retrofitted components [1]. One particular research gap is the need to develop modeling parameters and acceptance criteria for retrofitted components for use in performance-based seismic design (PBSD) standards such as ASCE 41-17 [2] and ACI 369 [3]. Another area of concern is the lack of consistency in measuring and reporting FRP material properties, both historically and continuing to this day [4]. The authors are engaged in broader research which involves developing a database of experimental tests on FRP-retrofitted RC shear walls and proposing modeling parameters for this component. However, the challenges related to inconsistency of FRP material property reporting have prevented a straightforward adoption of a design parameter, or predictor variable, related to FRP material properties into a regression model to develop the modeling parameters. The objective of this paper is to determine a design parameter related to FRP material properties to use in the development of modeling parameters for FRP-retrofitted RC shear walls.

Framework for the Development of Modeling Parameters

The framework shown in Fig 1 illustrates the process by which the authors are developing modeling parameters for FRP-retrofitted RC shear walls. The work began with the development of a database of FRP-retrofitted shear walls, where no such database existed prior. Next, backbone control points were determined from digitized envelope curves of each specimen. Key design parameters which have a significant impact on the response of each control point of interest were then identified. Design parameters act as predictor variables in regression models used to develop empirical equations, which is the last step in the framework.

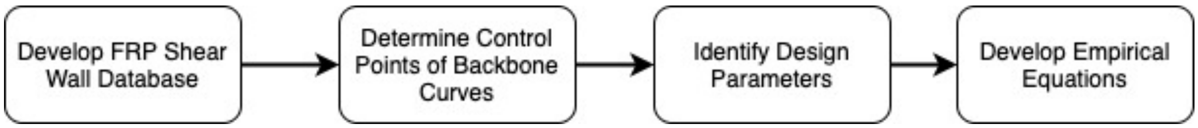

Figure 1: Framework for development of modeling parameters of FRP-retrofitted shear walls

FRP-Retrofitted Shear Wall Database

Dukes and Sattar [5] developed a database of FRP-retrofitted reinforced concrete shear walls. The database includes publicly available and accessible experimental tests on these walls globally, and currently contains over 150 wall specimens from 35 sources. Walls were distinguished by the presence of damage prior to FRP application (retrofitted (undamaged) vs repaired (damaged) and retrofitted), and the presence of openings in the specimens. This paper focuses on walls in the database that were retrofitted walls without openings.

Determine Control Points of Backbone Curves

The hysteretic responses of each specimen were extracted from the source document (journal paper, thesis, etc.) and digitized using a graphic digitizing software. Fig 2(a) shows an example of one such graph after digitization. Once the envelope of the hysteretic curve is digitized, key control points can be chosen for each specimen. Control points correspond to the force-deformation curves found in ASCE 41-17 [2]. Fig 2(b) shows the force-deformation curve typically used for walls controlled by shear in ASCE 41, which guides the development of control points for this project. Defining parameter *d*, the strength loss deformation parameter, is the focus of this work. Parameter *d* is defined as the drift at which there is a 20% drop in strength from the peak lateral load [6].

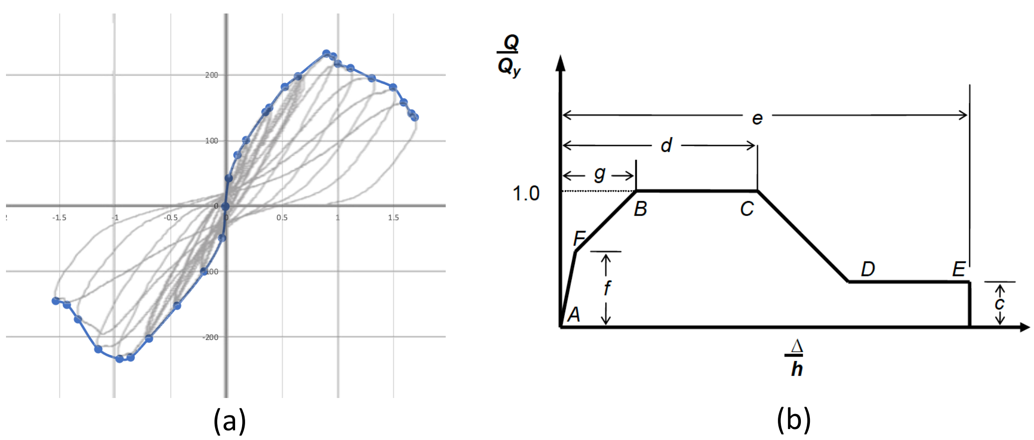

Figure 2: Backbone curve in the form of (a) envelope backbone curve of hysteretic response, and (b) Force-deformation backbone curve suitable for walls dominated by shear (ASCE 41-17).

Identify Design Parameters

Design parameters act as the predictor variables in the regression analysis used to develop empirical equations for predicting modeling parameters, such as the ASCE 41-17 parameter *d*. Therefore, choosing the correct design parameters is important to developing accurate modeling parameters. Initial design parameters were selected based on a review of modeling parameters of plain (unretrofitted) RC walls, available literature on experimental work on RC walls, and available guidelines for FRP retrofit. The design parameters for this work include axial load ratio, wall aspect ratio, and horizontal and vertical steel reinforcement ratios. Dukes and Sattar [5] provide definitions for each of these design parameters.

Develop Empirical Equations

The final step is to develop empirical equations for the proposed modeling parameters using regression analysis. The key design parameters will be the independent variables and the extracted backbone control points will be the dependent variable. Stepwise regression is used to reduce insignificant variables from the final equation, and a cross-validation method such as leave-one-out method will be used as validation of the model. The final modeling parameters will be published at a later date.

FRP Material Properties Challenges

Because these walls have an additional component that plain RC walls do not have (i.e. externally bonded FRP), there was a need to include a design parameter specific to FRP properties. There were several properties and combinations thereof that were investigated to find a suitable parameter to use in the empirical equations. The primary properties of FRP were Young's modulus (E), ultimate strength (f), and thickness (t). Problems arose once the discrepancies and differences in reporting properties became evident. The data sources from the database ranged from the late 1990s to date, and the way FRP material properties are measured and reported has changed. Even today, there isn't consistency amongst manufacturers on how material properties are measured and reported [4]. Often, sources reported either fiber properties or FRP composite properties, but not both. This results in the reduction of usable data points, which given the small size of the dataset, was not the desired outcome.

In an effort to address this issue, two options were considered: use only the data for which composite properties were reported (composite only model), or use the rule of mixtures to "convert" fiber properties to composite properties and combine the converted with the original composite properties (converted and combined model). The rule of mixtures is an approximation [7] shown by Equations 1-3, where "V" in the equations refers to volume of the material, "comp" refers to composite properties, "fib" to fiber, and "m" to the matrix or epoxy resin used in the FRP. If we assume that $E_m V_m$ is a small number, we can approximate that $E*t$ of fiber properties would equal $E*t$ of composite properties. As the number of data points with original composite properties is about 60 % of the available data, the composite only model uses a reduced dataset, while the converted and combined model uses the full dataset available.

$$E_{comp} = E_{fib}V_{fib} + E_m V_m \tag{1}$$

$$E_{comp} = E_{fib}\frac{t_{fib}}{t_{comp}} + \cancel{E_m V_m} \tag{2}$$

$$E_{comp}t_{comp} = E_{fib}t_{fib} \tag{3}$$

Results from Statistical Analysis to Compare Models

To decide between the two aforementioned options, regression models were developed using five design parameters related to the wall geometry and one FRP design parameter ($E*t$) The converted and combined model used $E*t$ of the data with original composite properties as well as the converted properties, and the composite only model used $E*t$ of the original composite properties only. The statistical measures p-value, R-squared, and Bayesian Information Criterion (BIC) were used to compare the models and select the more effective design parameter for FRP. The overall p-value of a regression model is the probability of obtaining the null hypothesis; in this case, the null hypothesis proposes that there is no difference between an intercept-only model (regression model without predictor variables) and the proposed model. If the p-value is less than a desired significance level, then the null hypothesis can be rejected. The R-squared, or coefficient of determination, value is a statistic used to measure the fit of a model, and it represents the percentage of the variation in the response variable that is explained by a model. The BIC is a statistical measure for the comparative evaluation of a finite set of models [8]. To compare different models, the model with the minimum BIC value is preferred. Table 2 shows the results of these statistics of the two models, one with converted FRP properties and the other model with only data points that had composite properties. Each statistical measure indicated the composite-only model is the preferred model. The authors believe the converted properties did not perform well because of the inconsistencies and discrepancies in reporting of fiber and composite properties of FRP and the resulting uncertainties introduced into the data by the conversion process. Based on these results, the authors chose to proceed with the composite only model. We did not conclude, however, that the rule-of-mixtures is not a valid approximation. We only conclude that for the dataset we have, the use of the approximation did not provide a better model for our purposes.

Table 1: Regression analysis and statistical measures of two models

Statistic	**Converted and Combined Model**	**Composite only Model**
p-value	0.21	0.005
R-squared	0.26	0.74
BIC	65.9	28.0

Conclusions

This paper presents the framework for the development of FRP-retrofitted RC shear walls and the challenges encountered in identifying an appropriate design parameters based on FRP material properties. The reporting of FRP material properties over the years has changed and is still not entirely consistently reported amongst manufacturers. This manifested in the data reported in the FRP-retrofitted shear wall database, mainly that some sources reported fiber properties and others reported composite properties, which are not readily converted. An investigation into two methods to address with this issue revealed that a regression model with a reduced dataset of composite only properties performed better based on the statistical measures of the p-value, R-squared value, and BIC than a regression model with a combined dataset of original composite properties and converted fiber-to-composite material properties. These results affect the development of modeling parameters by most leading to the use of a reduced dataset of composite only properties. The results of this analysis also highlights the need for consistency in reporting of FRP-properties across manufacturers and labs in order to avoid problems of comparisons of performance of retrofitted structures.

References

1. Goodwin, D, Sattar, S, Dukes, J, Kim, JH, Sung, L, and Ferraris, C. Research Needs Concerning the Performance of Fiber Reinforced (FR) Composites Retrofit Systems for Buildings and Infrastructure. *NIST Special Publication* 1244, 2019. https://doi.org/10.6028/NIST.SP.1244
2. ASCE/SEI Standard 41-17. *Seismic Evaluation and Retrofit of Existing Buildings*. American Society of Civil Engineers: Reston, VA, 2017.
3. ACI Committee 369. Standard Requirements for Seismic Evaluation and Retrofit of Existing Concrete Buildings (369.1) and Commentary. American Concrete Institute, Farmington Hills, MI, 2017.
4. Arnold, SF, and Ortiz, R. Myths and Fallacies Related to the Determination of Design Values for FRP Systems. *Proceedings of SEAOC Convention*. San Diego, CA, 2021.
5. Dukes, J, Sattar, S. A Database of Test Results From Experiments on FRP-Retrofitted Reinforced Concrete Shear Wall. *Earthquake Spectra*. (submitted for review).
6. Abdullah, SA, Wallace, JW. Drift Capacity of Reinforced Concrete Structural Walls with Special Boundary Elements. *ACI Structural Journal*, V. 116, No. 1, January 2019.
7. Rasheed, H. *Strengthening Design of Reinforced Concrete with FRP.* CRC Press, 2014.
8. Profillidis, VA, and Botzoris, GN. Chapter 6 - Trend Projection and Time Series Methods. *Modeling of Transport Demand.* Edited by VA Profillidis, GN Botzoris. Elsevier. 2019. Pp 225-270.