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REINFORCED CONCRETE STRUCTURAL WALL DATABASE DEVELOPMENT FOR MODEL VALIDATION

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ABSTRACT

Reinforced concrete walls are commonly selected as the lateral resisting systems in seismic design of buildings. The design procedure requires reliable/robust models to predict the wall response. Many researchers, thus, have focused on using the available experimental data to be able to comment on the quality of models at hand. What is missing though is an uncertain attitude towards the experimental data since such data can be affected by different sources of uncertainty. In this paper, we introduce the database created for model quality evaluation purposes considering the uncertainties in the experimental data. This is the first step of a larger study on experience-based model quality evaluation of reinforced concrete walls. Here, we briefly present the database as well as six sample validations of the developed numerical model (the quality of which is to be assessed). The database contains the information on nearly 300 wall specimens from about 50 sources. Both the database and the numerical model, built for uncertainty/sensitivity analysis purposes, are mainly based on ten parameters. These include geometry, material, reinforcement layout and loading properties. The validation results prove that the model is able to predict the wall response satisfactorily. Consequently, the validated numerical model could be used in further quality evaluation studies.

INTRODUCTION

Among the earthquake resistant structural members, reinforced concrete (RC) structural walls are of high importance. Not only because of the considerable stiffness they offer, but also due to their capability to stand large strength/ductility demands in case of proper design. The mentioned 'proper design' is more likely to be achieved via the new performance-based design procedures in which the desired performance under specific seismic hazard is sought. This requires hazard, structural, damage and loss analysis. On one hand, the mentioned procedures are affected by uncertainties in the loading and structural properties. On the other hand, they are all susceptible to modelling disqualification/unfitness. In the former case, probabilistic approaches have evolved in order to deal with the uncertainties [1, 2, 3 & 4]. In the latter case, experimental data is commonly used as benchmark for model validation [5, 6, 7 & 8].

Yet, experimental data can be used not only for model validation but also for model calibration and empirical studies. Collecting such data and organizing it in databases facilitates data management/usage as well as stochastic analysis on the data. In the case of RC walls, for instance, many researchers created databases of wall experiments in order to study different aspects of wall behavior. Tuna [9], for instance, developed a database of 124 walls with the purpose of studying the

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effects of a set of selected parameters on shear and deformation capacity of RC walls. The data, taken from 19 different sources, included information about loading and section type, geometry, shear span ratio, axial load ratio and reinforcement properties. Gulec and Whittaker [10] assembled a database including 434 squat walls with three different cross sections based on loading type, aspect ratio, shear span ratio, axial load ratio, material properties and type of failure. The goal was to find out which factors affect the performance of the wall and to introduce new models capable of simulating the wall behavior. Birely [11] collected the data from 66 slender wall specimens. The data was organized according to geometry and reinforcement properties, loading type and shear strength. The database was built to create fragility functions for slender walls with the shear span ratio of greater than or equal to 2.0.

What might be disregarded in experimental studies, though, is that experiments can be as fragile as the numerical simulations. In fact, uncertainties can as well affect the experimental data. Therefore, a proper model quality evaluation through validation against experimental data should take the uncertainties into account. In this paper, we present the RC wall experimental database developed with the purpose of model quality assessment of RC walls considering uncertainties in experimental data. The collected data taken from several specimens was organized in a way to be compatible with the input/output parameters of the parallel numerical study. The resulting database contains information regarding the geometry, material, reinforcement layout and loading properties of the specimens. The model quality evaluation based on the developed database is the focus of an ongoing research by the first author. With proper model quality evaluation strategies we can avoid using unfit models in analysis/design procedures. This leads to more reliable and robust designs.

In the following sections, we first describe the database including the sources in the technical literature and the information collected from each source. Second, we make comparisons between the results of a developed RC wall model and samples from the database. The last section contains the concluding remarks on the presented study.

DATABASE DEVELOPMENT

The database was created as part of a study on model quality assessment of RC structural walls. The basic idea was to collect the information available in the literature in order to analyze the uncertainty properties of the experimental data in the process of evaluating the quality of the desired numerical model. Several sources were selected from the literature. There was an attempt to include sources from a variety of authors, years and types (Papers, Thesis and Reports). Some of the already available databases and statistical studies were searched for references to potential sources [9, 10 & 11 among others].

In sum, a total of 48 sources and nearly 300 specimens were chosen as presented in Table 1. The table includes the authors, section/wall type, number of specimens considered and the references to the corresponding sources. The type of wall was determined based on FEMA356 [12] where walls with aspect ratios less than 1.5 and greater than 3.0 are defined as squat and slender walls, respectively. Out of the 298 walls, 202 were squat whereas 15 were slender. A total of 81 walls fell in the transition category in between the squat and slender walls. This information was later used to calculate the nominal yield displacement of the walls. With respect to the type of the wall section, an almost equal distribution between the rectangular and barbell/flanged walls was observed. This corresponds to 56 and 44 percent of the total number of walls, respectively. The majority of the walls contributing to a percentage of 77 were cyclically loaded. Subsequently, 17 and 6 percent of the total walls were, in the same order, tested under monotonic and dynamic loads.

A very important step in the database development was to determine the parameters to be collected. This should be done considering the purpose of creating the database being the model quality evaluation of RC structural walls. There was a need to be able to perform uncertainty analysis on the experimental data along with the numerical simulations in a comparable way. Thus, the variable parameters in the database and the numerical simulation had to be the same. It was ideal to select the minimum number of parameters providing the most information regarding the walls. The required information included geometry, material, reinforcement layout and loading properties of the walls. Consequently, ten parameters were selected in which three were used to define the geometry of the wall, two included information regarding the material properties, four specified the reinforcement layout. The last parameter was used to record the axial loading. All the recorded parameters are presented in Table 2. Some of the variables required for the definition of these parameters are described in the modeling section. It should be noted that for most of the parameters a normalized value was preferred in order to make comparisons easier. As seen in Table 2, except for concrete compressive strength and steel yield strength which are generally not very discrepant, all parameters were normalized based on well-known methods.

Table 1. Database sources.

		Section type		Wall type					Section type		Wall type		
Authors	No. Specimens	Rectangular	Barbell/Flange	Squat	Slender	Reference	Authors	No. Specimens	Rectangular	Barbell/Flange	Squat	Slender	Reference
Dazio et al.,	6		✓		✓	[13]	Lassy & Mitchel	2	✓			✓	[36]
Thomsen &Wallace	2		✓		✓	[14]	Tasnimi	4	✓			✓	[37]
Oesterle et al.	12	✓	✓		✓	[15]	Palermo	2		✓	✓		[38]
Escolano-Margarit et al.	2	✓	✓		✓	[16]	Wiradinata	2	✓		✓		[39
Tran &Wallace	5		✓	✓	✓	[17]	Tupper	1		✓		✓	[40]
Sittipunt et al.	4		✓	✓		[18]	Bouchon et al.	3		✓	✓		[41]
Lestuzzi &Bachmann	6	✓			✓	[19]	Sanada & Keabeyasawa	2		✓	✓		[42]
Mansour and Hsu	12	✓		✓		[20]	Rothe & König	11		✓	✓		[43]
Salonikios et al.	11			✓		[21]	Takahashi et al.	17		✓	✓		[44]
Massone et al.	14	✓		✓		[8]	Shiga et al.	5		✓	✓	✓	[45]
Cardenas et al.	7	✓		✓		[5]	Paulay & Goodsir	3	✓			✓	[46]
Barda et al.	8		✓	✓		[22]	Lefas et al.	13	✓		✓	✓	[47]
Hildago et al.	26	✓		✓	✓	[23]	Yanez et al.	1	✓		✓		[48]
Maier	9	✓	✓	✓		[24]	Kim & Foutch	5	✓	✓	✓	✓	[49]
Choi	6	✓	✓	✓		[25]	Kabeyasawa & Matsumoto	6		✓		✓	[50]
Cardenas et al.	6	✓			✓	[26]	Endo et al.	20		✓	✓		[51]
Lefas &Kotsovos	7	✓			✓	[27]	Shiu et al.	1	✓			✓	[52]
Zhang & Wang	4	✓			✓	[28]	Shimazaki	1	✓			✓	[53]
Mansur &H'ng	5		✓	✓		[29]	Pinho	3	✓			✓	[54]
Stevens et al.	3	✓		✓		[30]	Ile et al.	3	✓			✓	[55]
Gupta & Rangan	8		✓	✓		[31]	Lowes et al.	4	✓		✓		[56]
Ghorbani-Renani et al.	4	✓			✓	[32]	Hiraishi et al.	2		✓		✓	[57]
Lopes	3	✓		✓		[33&34]	Lombard	1	✓		✓		[58]
Mickleborough et al.	6	✓		✓	✓	[35]	Athanasopoulou	9	✓		✓		[59]

Table 2. Recorded parameters in the database.

Parameter	Definition
H/L	Wall aspect ratio
A_b/A [1]	Boundary area ratio
L_b/L	Boundary length ratio
$\rho_{vw} = A_{svw}/A_w$ [2]	Web vertical reinforcement ratio
$\rho_{hw} = A_{shw}/s_w t_w$ [3]	Web horizontal reinforcement ratio
$\rho_{vb} = A_{svb}/A_b$ [2]	Boundary vertical reinforcement ratio
$\rho_{hb} = A_{shb}/s_b t_b$ [3]	Boundary horizontal reinforcement ratio
$f_c^{'}$	Concrete compressive strength [MPa]
f_y	Reinforcement yield strength [MPa]
$P/(f_c^{'} \cdot A)$	Axial load ratio

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[1] A_b : Boundary area and A : area of the section

[2] A_{svw} (A_{svw}) : Web (Boundary) vertical reinforcement area and A_w : Web area

[3] A_{shw} (A_{shb}) and s_w (s_b) : Web (Boundary) horizontal reinforcement area and spacing

In addition to the input parameters, several output parameters were chosen to be recorded in the database. The outputs would later be used in the uncertainty analysis of the experimental data and quality assessment of the desired numerical model. For this purpose, the force-deformation relationships of the specimens (when available) were collected in the form of force and deformation vectors. Commonly, the aforementioned relationship was presented as plots. The desired information was therefore attained by digitizing the plots. The maximum shear and the corresponding displacement recorded for each specimen were also added to the database. These outputs were later used in order to perform a basic validation of the numerical model against the experimental data. In order to provide a glimpse on the relation between the outputs and the inputs the output-input correlation coefficients are presented. Figure 1 shows the correlation coefficients of the normalized maximum shear with respect to all the considered input parameters for three different types of walls. It is clear that the type of the wall affects the correlation with different parameters. For squat walls, as an example, the geometrical properties have the major influence on the output. For transition walls, however, the material and loading properties become more influential. In the case of slender walls the pattern is totally different. Here, section type and the reinforcement properties play the main roles. The aforementioned patterns are in well agreement with previously performed studies [9].

Finally, the nominal yield displacement was calculated for each wall based on formulations from [60] and [61] for squat and slender walls respectively. The yield displacement along with the recorded displacement at peak were then used to find the ductility of each wall. Other information such as the type of failure and the quality of the source was additionally entered in the database.

MODEL VALIDATION

As mentioned before, the database was created as part of a model quality evaluation study. In the first step, the numerical model (the quality of which had to be assessed) was validated against experimental data. In this section, samples of the aforementioned validation are presented. The numerical model was built based on the Multiple Vertical Line Element Model (MVLEM) using the OpenSees [62] platform (See Figure 2). In this model the vertical line elements generate the wall behavior in flexure whereas the shear spring contributes to the shear behavior. It should be noted, though, that the model in its current conditions does not seem to be an appropriate choice for the modeling of squat walls where the shear behavior dominates the response.

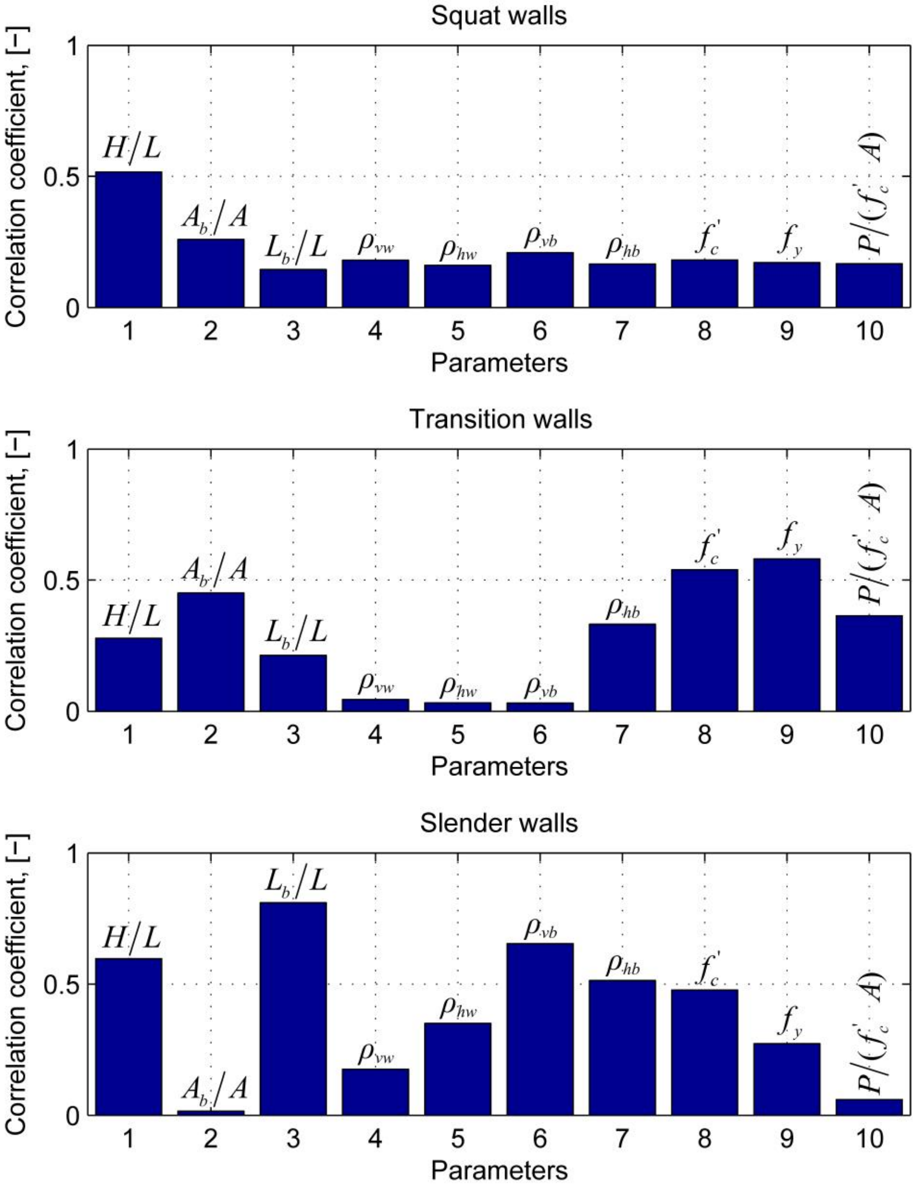

Figure 1. Output-input correlation coefficients for three different wall types.

The deficiency of the model in properly capturing the shear behavior was also noticed in some of the sample validations made for walls with aspect ratios below 1.5. In these cases the model failed to produce comparable results to the experimental response. Therefore, here mainly the results for slender walls with aspect ratios more than 2.0 are presented. The current model needs to be improved in order to appropriately capture the shear behavior. This is to be done in the ongoing study.

The OpenSees model, as seen in Figure 2, contained *truss*, *zeroLength* and *elasticBeamColumn* elements. *truss* elements with fiber sections were used to define the vertical lines. This allowed for distributed plasticity along the elements length. *concrete02* and *steel02* specified the material properties of the fibers. *zeroLength* elements were used as the shear springs at 0.4 times the height of each wall segment. Properties of the shear springs were found according to [60]. The whole system of vertical truss elements and shear springs was integrated by means of rigid columns in the middle and rigid beams at the level of each segment. Further information on modeling can be found in [63 & 64]. In order to ease the following uncertainty analysis on the model output, a Matlab [65] code was used to create OpenSees models and perform the analysis. The same ten parameters as the ones in the database (Table 2) were defined as the main parameters of the models in the Matlab code.

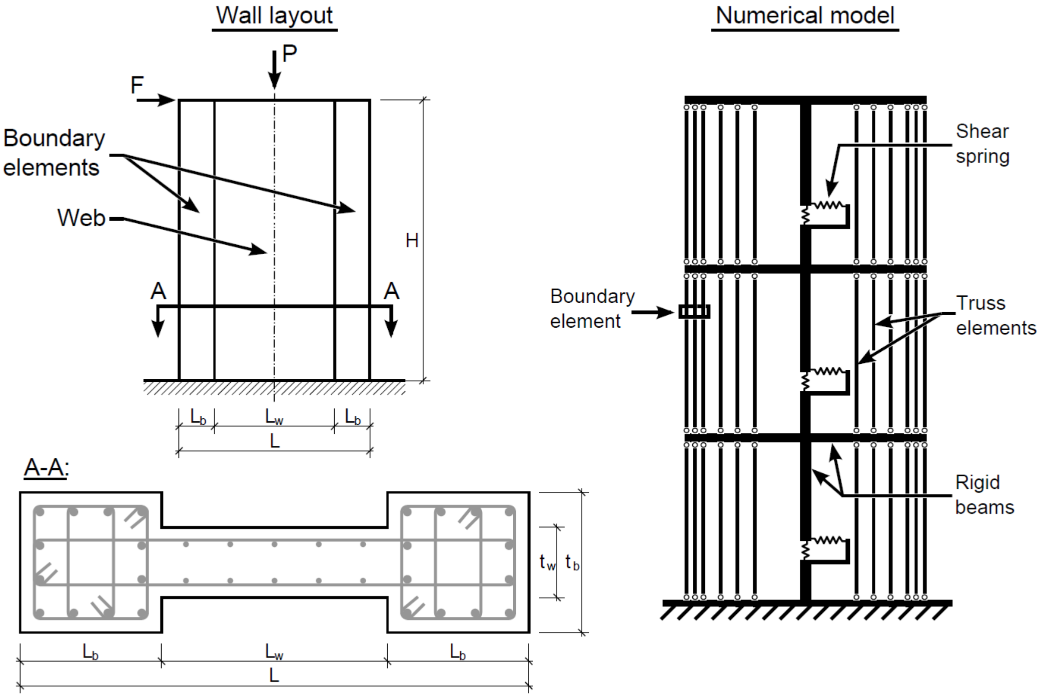

Figure 2. The wall layout and the corresponding numerical model [63].

Six sample validations are shown in Figure 3. Here, the force-deformation plots are presented in the normalized format. The base shear was divided by the nominal shear capacity calculated based on [61]. Similarly, the top displacement was divided by the wall height to produce the drift. In cases where the experiment was performed under cyclic loading the corresponding force-deformation envelope in the positive direction was considered for the comparison. As it can be observed from Figure 3, the agreement between the responses predicted by the numerical model and the experiments is very promising. It should be emphasized that the model is mainly built based on ten parameters (See Table 2). Therefore, arriving at results close to the experimental response provides evidence that the choice of the main parameters was appropriate and the model could be forwarded for further quality evaluation studies.

CONCLUSIONS

The RC wall experimental database developed for model quality assessment purposes along with sample validations of the numerical model to be assessed were presented. The database contains the information on nearly 300 wall specimens from about 50 sources. The main input parameters include the aspect ratio, boundary area/length ratio, web and boundary vertical/horizontal reinforcement, concrete's compressive strength, steel yield strength and axial load ratio. The database and the accompanying numerical model were created as parts of larger study on experience-based model quality evaluation of RC walls. The main feature of this study is the focus on uncertainty properties of experimental data. So, the experimental data is not considered as the reality but rather an uncertain abstraction of it, just as the numerical models. The numerical model to be assessed was also introduced here and some sample validations of it against the database entries were presented. The model provided promising results in comparison to the experimental response and therefore proved to be suitable for further model quality evaluation studies.

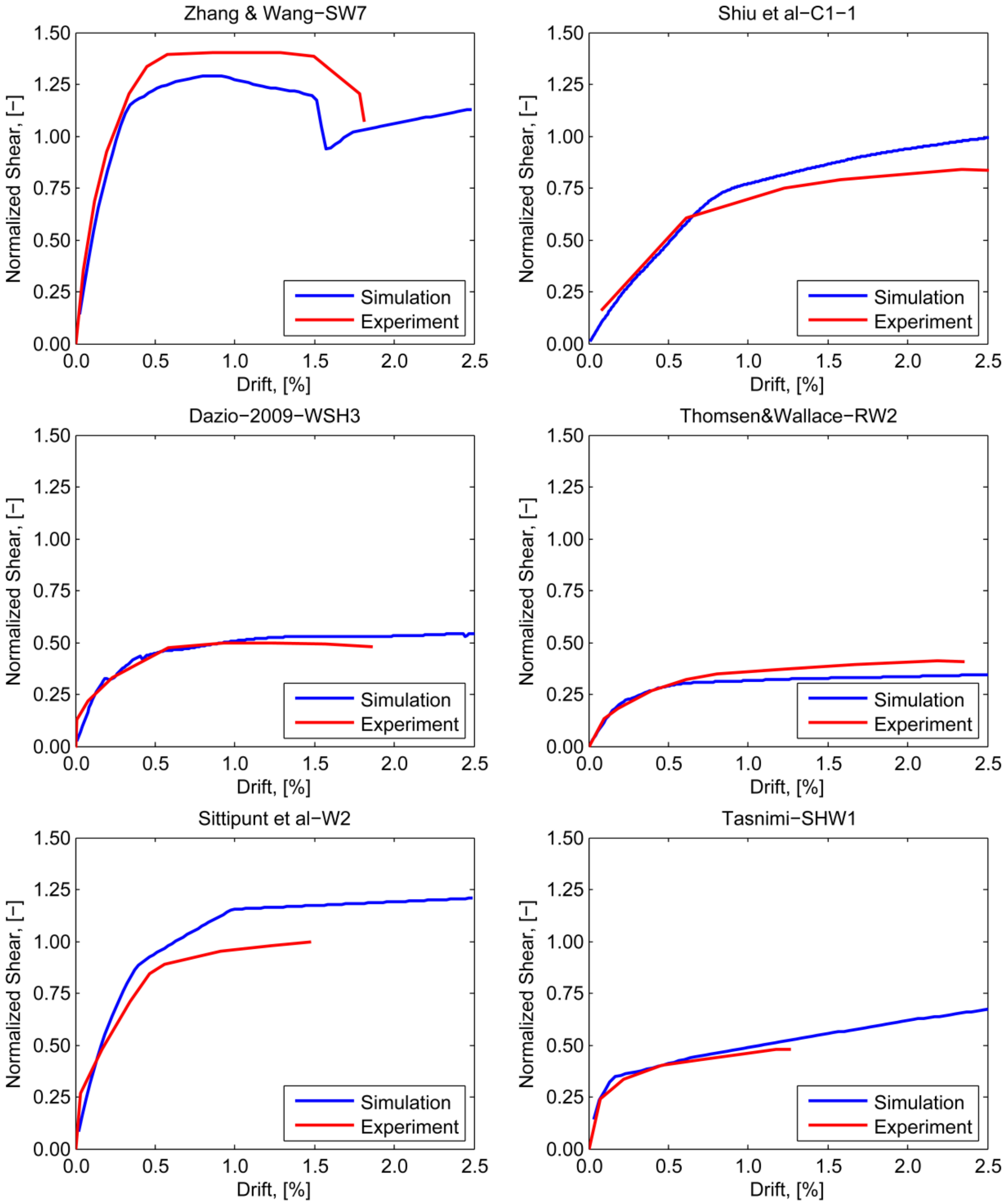

Figure 3. Model validation against selected entries of the developed database.

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