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MODEL QUALITY EVALUATION OF COUPLED RC FRAME-WALL SYSTEMS FOR GLOBAL DAMAGE ASSESSMENT

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Abstract. *Civil engineers take advantage of models to design reliable structures. In order to fulfill the design goal with a certain amount of confidence, the utilized models should be able to predict the probable structural behavior under the expected loading schemes. Therefore, a major challenge is to find models which provide less uncertain and more robust responses. The problem gets even twofold when the model to be studied is a global model comprised of different interacting partial models. This study aims at model quality evaluation of global models with a focus on frame-wall systems as the case study. The paper, presents the results of the first step taken toward accomplishing this goal. To start the model quality evaluation of the global frame-wall system, the main element (i.e. the wall) was studied through nonlinear static and dynamic analysis using two different modeling approaches. The two selected models included the fiber section model and the Multiple-Vertical-Line-Element-Model (MVLEM). The influence of the wall aspect ratio* (H/L) *and the axial load on the response of the models was studied. The results from nonlinear static and dynamic analysis of both models are presented and compared. The models resulted in quite different responses in the range of low aspect ratio walls under large axial loads due to different contribution of the shear deformations to the top displacement. In the studied cases, the results implied that careful attention should be paid to the model quality evaluation of the wall models specifically when they are supposed to be coupled to other partial models such as a moment frame or a soil-footing substructure which their response is sensitive to shear deformations. In this case, even a high quality wall model would not result in a high quality coupled system since it fails to interact properly with the rest of the system.*

1 INTRODUCTION

In the field of civil engineering the goal is to design structures that, with a certain amount of confidence, will be able to fulfill their purpose of construction i.e. withstand loading and deformation schemes the structure is expected to undergo during its lifetime. In other words a civil engineer aims at designing reliable structures by examining the *probable* response of the structure under *expected* loading conditions. Such terms are normally observed in the civil engineering technical literature due to the facts that the human knowledge about the nature of the phenomena underlying the structural behavior is limited and that many phenomena even have randomness as their inherent characteristic. Consequently, any model which is an abstraction of the phenomena to be studied, also faces deficiencies in terms of knowledge i.e. *uncertainties*. Finding models that can be employed as tools to further design reliable structures has therefore turned into a challenge. As a solution, *model quality criteria* are defined which allow for making decisions over a range of plausible models. Since most of the engineering models, when possible, are discretized into smaller distinct but coupled parts (so called partial models) to ease their study, the model quality evaluation originally starts from the partial models and their coupling. The ongoing study, conducted by the first author, aims at evaluating the global model quality of coupled partial models for damage assessment purposes considering the quality of the partial models and their coupling. To find a general solution coupled reinforced concrete (RC) frame-wall systems are studied as an example of widely used coupled structural systems. In the present study, the model quality evaluation process is started by investigating the wall models since the wall element is the crucial partial model in the coupled system. Based on a literature survey, two of the well known modeling approaches, namely the fiber section model and the Multiple-Vertical-Line-Element-Model (MVLEM) were chosen for further studies. To take the first step, the model responses under cyclic deformation-controlled loading are compared to a selected observed response. To further investigate the differences, the models responses are then compared through static and dynamic analysis. Finally, the results are discussed and conclusions are derived.

2 MODEL QUALITY EVALUATION OF COUPLED SYSTEMS

The main challenge in the model quality evaluation process is to prove the model to be an appropriate representative of the real structural system for its intended purpose of use. The difficulty gets even twofold in the absence of adequate observed data from real and experimental systems to validate the global model. For the specific case of a frame-wall system, for instance, almost negligible amount of experimental data is available for the coupled system (particularly in interaction with the soil-footing substructure). Although, an extensive number of experiments can be found in the literature individually focused on wall or frame elements. So, one of the primary challenges in the field of frame-wall systems, is to validate the global model when there is only a chance to validate its partial models against experimental data. In fact RC structural walls have gained considerable attention in the construction/rehabilitation of new/existing buildings in regions with medium to high seismic hazard. This is mainly because: they provide structures with lateral stiffness, strength and ductility if properly designed/constructed and they have shown reasonable performance during the past earthquakes. In the most common building configuration, the RC walls are combined with a gravity resisting system (usually RC moment frames or slabs) to form an integrated lateral/vertical load-carrying system. In such frame-wall structures the most lateral resisting of the system is supplied by the walls. Therefore, their modeling and design becomes a critical issue, since the structural performance under

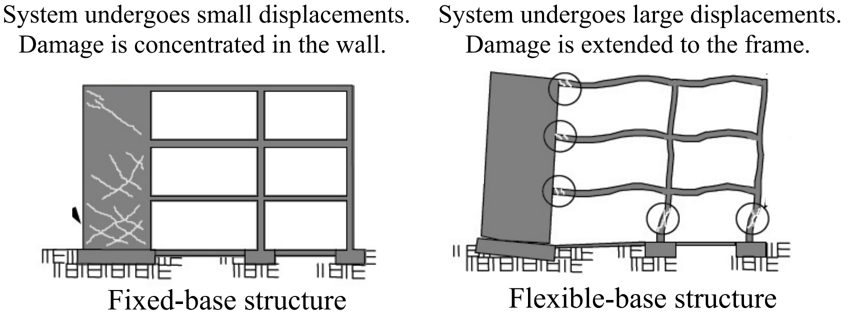

Figure 1: Structural response of a coupled frame-wall system in the presence/absence of the couplings (Originally from [1])

seismic actions relies mainly on their performance. Nevertheless, it has been learned from the past earthquakes that the wall performance can be significantly affected by the interactions with other substructures (see Figure 1).

So far, it is quite well understood that neglecting the coupling effects may lead to a misestimation of the structural response/damage. In spite of being aware of this, however, it has been a common practice to ignore the interaction among the substructures in frame-wall systems. The absence of adequate observed data for the global model to be validated on one hand and the complexity of the available models which does not allow for parametric studies on the global model on the other hand may be the main reasons. For instance, many researchers have focused on the study of RC walls ([28, 11, 13, 19, 5, 12, 6, 18, 15, 24] among the others) whereas quite a few have investigated the coupled frame-wall systems particularly in interaction with the soil-foundation substructure ([23, 3, 16, 27, 21, 26, 4] among the others). Evidently, there is still a crucial need to quantitatively measure the importance of coupling effects by means of tools like the sensitivity analysis. Based on the results from a sensitivity analysis one can decide whether or not the global model under study can be reduced to its partial models by disregarding some uninfluential parameters/aspects/interactions.

3 MODELING APPROACHES

The global model of the system to be studied is constructed by means of coupling different partial models. The choice of a specific modeling approach not only depends on the capabilities of the resulting partial model in representing a part of the whole system, but also on its capacity to interact properly with the rest of the system. In other words, when dealing with global models, the *high quality* of a partial model does not necessarily signify that its application will lead to a *high quality* of the global model. In fact, in cases where the desired degree of coupling to the other partial models can not be reached, the overall quality may even decrease. Finally, one also has to consider the amount of computational time and effort to be supplied when selecting a model out of a number of plausible models.

In the superstructure of a RC frame-wall system at least two partial models can be distinguished, namely: the wall and the frame. According to the technical literature, the numerical modeling of RC frame elements has been well developed ([7, 17, 25, 8] among the others). Distributed and lumped plasticity elements are widely being used to analyze and design RC frames. Distributed plasticity models are mainly based on the fiber section concept which allows for the interaction between flexural and axial behaviors. Models based on this concept provide powerful tools for the analysis of RC frame elements in which the shear deformations are roughly ignorable. The main challenge, however, is to find an appropriate model for the wall element.

Numerous micro/macro models have also been proposed for structural walls ([10] reviews a selected number of the available models). According to the technical literature, the most efficient models, in terms of the capabilities and accuracy on one hand and the required computational time and cost on the other hand, are based on the fiber section concept. This modeling method is considered as a *micro-modeling* approach and thus is able to predict both local and global damages in the wall. The main drawback is that since fibers only undergo axial deformations the model fails to detect shear deformations. This may result in unrealistic predictions of the wall response in the case of squat walls (i.e. aspect ratios less than 2.0, as a practical criteria). Not to mention that the model also fails to consider some observed phenomena like neutral axis shift. To further develop the method macro models have been proposed which not only benefit from the fiber section concept but also from some additional features that cover the shortcomings of the fiber section method. “Multiple Vertical Line Element Model (MVLEM)” is one of the well known solutions. Fibers are individually defined as ’vertical line elements’ over the section and a shear spring is added to allow for deformations under shear actions. Although in this case, no interaction between the flexural and shear behaviors is considered which seems to be inconsistent with experimental observations according to [19]. Nevertheless, the MVLEM constructed through the above-mentioned procedure provides a powerful tool to predict RC wall behavior under lateral loadings.

The basic concept for creating the MVLEM is to separate the flexural and shear behaviors of the wall element (see Figure 2). Here the two modes of deformation are assumed to be uncoupled. The flexural and axial behaviors of the wall (and their corresponding interaction) are represented by the contribution of fibers whereas the shear spring constitutes the behavior under shear actions. Relative rotation of the upper bound of the wall to its base is defined by considering a center of rotation. The point is located on the central column of the element at a specific height ch where h is the height of the wall (see Figure 3). c is practically set to be 0.4 for common applications [28]. It is however recommended to include more elements along the height of the wall where significant nonlinear behavior is expected. This is to avoid curvature misestimations in the regions where it is highly variable [8]. Although, the total number of divisions along the height or the length of the wall does not have a significant effect on the overall behavior of the wall. Nevertheless, by adding more elements it is more likely that one can detect the desired local behavior/damage [15, 20].

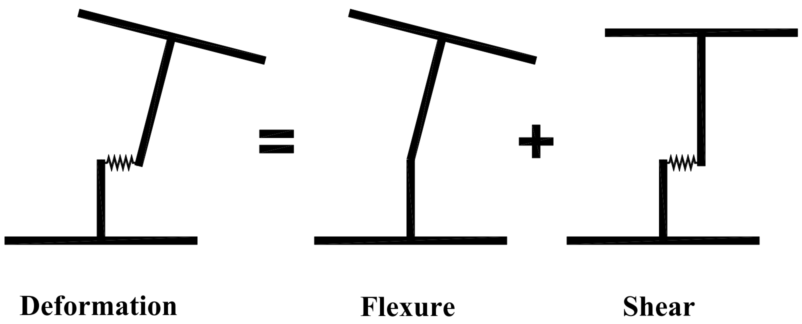

Figure 2: Schematic deformation decoupling of a RC wall element in MVLEM [19]

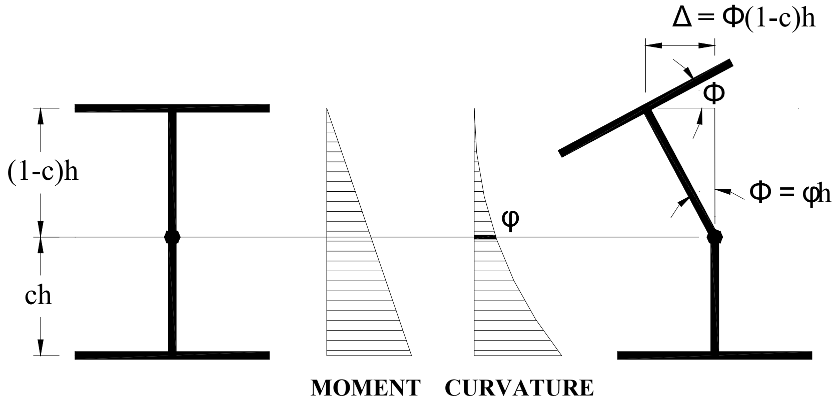

Figure 3: Center of rotation in MVLEM [19]

Quite well known material models are available for concrete (e.g. Kent-Scott-Park model with tensile strength) and steel (e.g. Menegotto-Pinto model) to define the vertical line elements' sectional force-deformation relationships under axial actions. There are also a handful of choices for the hysteretic behavior to be assigned to the shear spring i.e. the sectional force-deformation relationship under shear actions ([16, 9, 19, 29, 15]). Here, the major concern is to represent the low hysteretic energy absorbtion capability in shear. Mostly, this is done by means of origin-oriented or pinching hysteretic materials. In this study a pinching hysteretic material with a trilinear backbone curve was used. Its behavior under cyclic loading is determined by means of some predefined rules. The cracking and yield properties of the backbone curve were calculated according to [16, 22]. The aforementioned hysteretic material allows for pinching of force and deformation, damage due to ductility and energy, and degraded unloading stiffness based on ductility. More details about hysteretic materials can be found in [14].

To study the MVLEM the results from static monotonic and cyclic as well as dynamic analysis of the model were compared to the corresponding results of a fiber section model. Both models were created and analyzed using the OpenSees platform. The fiber section model consisted of a single column defined with *nonlinearBeamColumn* element to which a fiber section was assigned. *Concrete02* (Kent-Scott-Park model with linear tension softening) and *Steel02* (Giuffre-Menegotto-Pinto model) were chosen to represent the constitutive material relationships of the concrete and the reinforcing steel, respectively. In order to consider the deformations due to shear, the force-deformation relationship of the section under shear actions was separately calculated as discussed before and was added to the previously defined fiber section. To create the MVLEM, two MVLEM sets were stacked along the height of the wall each having half the height of the wall. Each of the MVLEM sets consisted of 11 truss elements to which fiber sections with the same material properties as those of the fiber section model were assigned. The truss elements were connected by means of rigid beams at their end nodes. The central columns were divided into two rigid parts at 40% of their heights. Horizontal (shear) and vertical springs were defined to connect the two parts of each central column. The shear spring properties were calculated in the same manner as those of the fiber section model. The two models created through the abovementioned procedures are schematically shown in Figure 4. The numerical results will be presented in the following section.

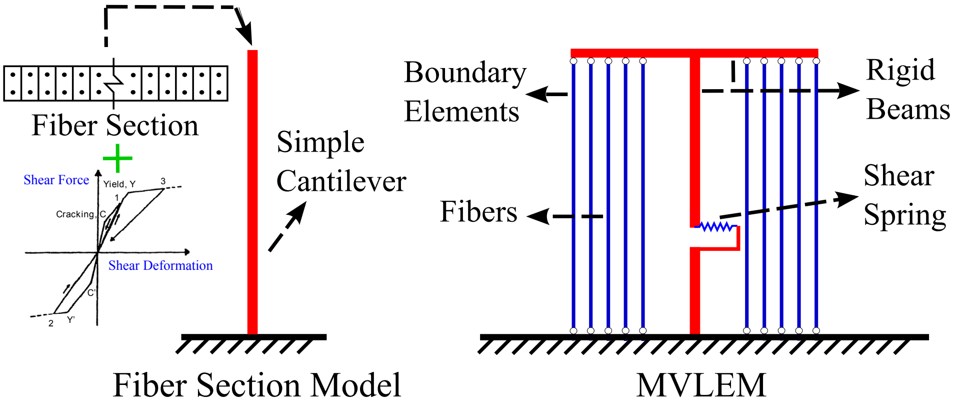

Figure 4: The two studied models: the fiber section model and the MVLEM

4 NUMERICAL RESULTS: MVLEM VS FIBER SECTION MODEL

To take the first step, the MVLEM was verified/validated against observed response of a selected wall specimen to check its potential for further studies. For this purpose, the specimen WSH3, one of the 6 wall specimens tested within an experimental program conducted at the ETH Zurich [6], was chosen as the reference experimental model. During the test the specimens were subjected to a deformation-controlled quasi-static cyclic loading. Details about the loading schemes can be found in [6]. The WSH3 with a height of $4.56m$ had a rectangular section of $2.0m$ length and $0.15m$ thickness. The reinforcement layout is shown in Figure 5. Compressive strength (f'_c) and modulus of elasticity (E_c) for concrete were reported to be 39.2 MPa and 35.2 GPa, respectively. Also, the yield strength of steel (f_y) for boundary and web reinforcements were respectively recorded to be 601.0 MPa and 569.2 MPa. Additional information about the sectional and material properties can be found in [6]. It is worth mentioning that throughout the rest of the study the sectional and material properties are kept unchanged. Comparison of the results from this step are presented in Figure 6. Very good agreement can be seen between the three responses (i.e. MVLEM, fiber section model and the experimental results). The model was therefore qualified to be used for further sensitivity/uncertainty studies.

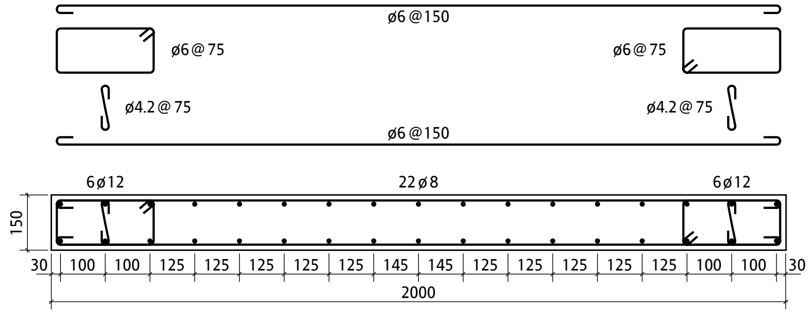

Figure 5: Reinforcement layout for the WSH3 specimen [6]

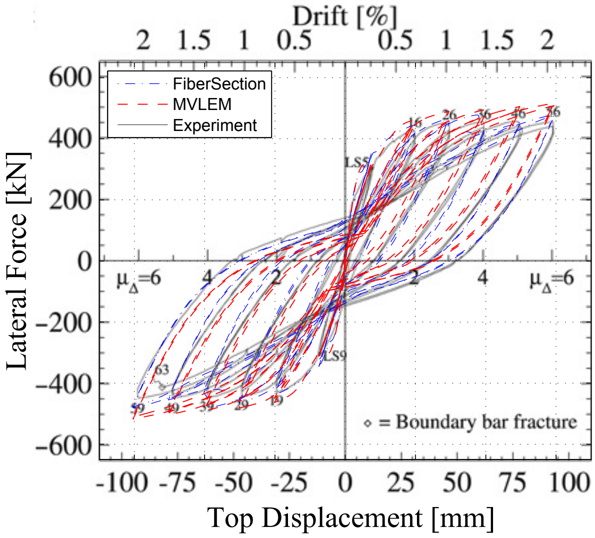

Figure 6: Static cyclic analysis results of the two studied models compared to the experimental results for the WSH3 specimen from [6]

In the next step, sensitivity analysis was used to find out the influence of the wall aspect ratio (H/L) and the amount of the axial load (P) on the response of the wall. The mentioned parameters are known to have noticeable effects on the response of wall elements. The two variables were assumed to have uniformly distributed probability densities over their entire ranges ($[1.0-3.0]$ for the wall aspect ratio and $[100.0-1500.0]$kN for the axial load). Latin Hypercube Sampling method was used to generate 400 samples for the pushover analysis and 100 samples for the dynamic analysis from the marginal probability distributions of the variables. Figure 7 shows the distribution of the studied samples in the case of the dynamic analysis. In the next sections the nonlinear static and dynamic analysis results from the two studied models will be presented, compared and discussed.

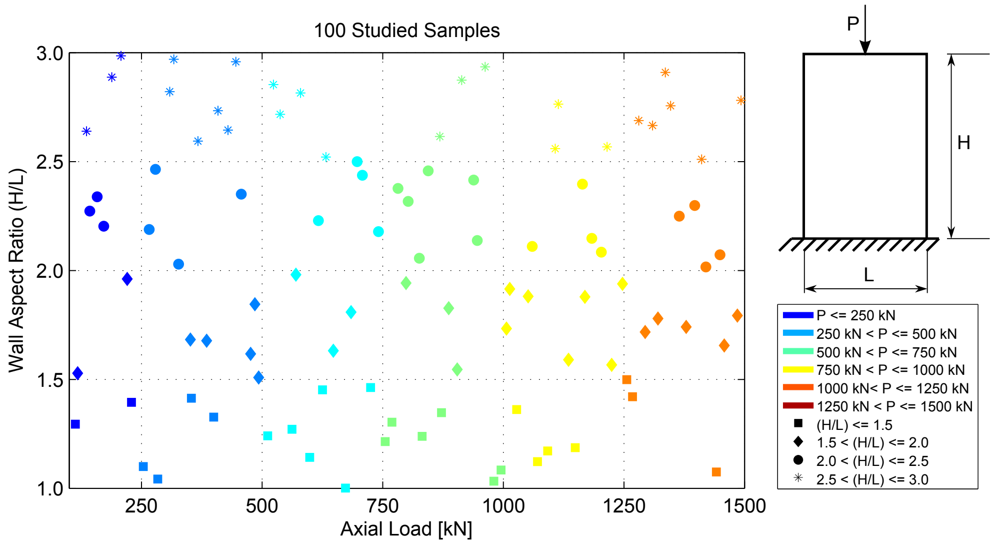

Figure 7: Distribution of the studied samples for the dynamic analysis with regard to the variables

4.1 Static Monotonic Analysis (Pushover)

Primarily, gravity analysis was performed for each model under the sampled axial load. A displacement-controlled pushover analysis was then performed until the top displacement (controlled displacement) reached 2% of the height for each model (2% drift was roughly taken as the failure drift). The resulting pushover curves (i.e. base shear vs top displacement curves) of both the MVLEM and the fiber section model are shown in Figure 8 for 400 samples. As it is obvious from the figure, the models have resulted in similar response curves in the case of less stiff walls (i.e. walls with aspect ratios greater than 2.0). However, failure in fiber section models with aspect ratios less than 2.0 signifies a noticeable difference between the two models.

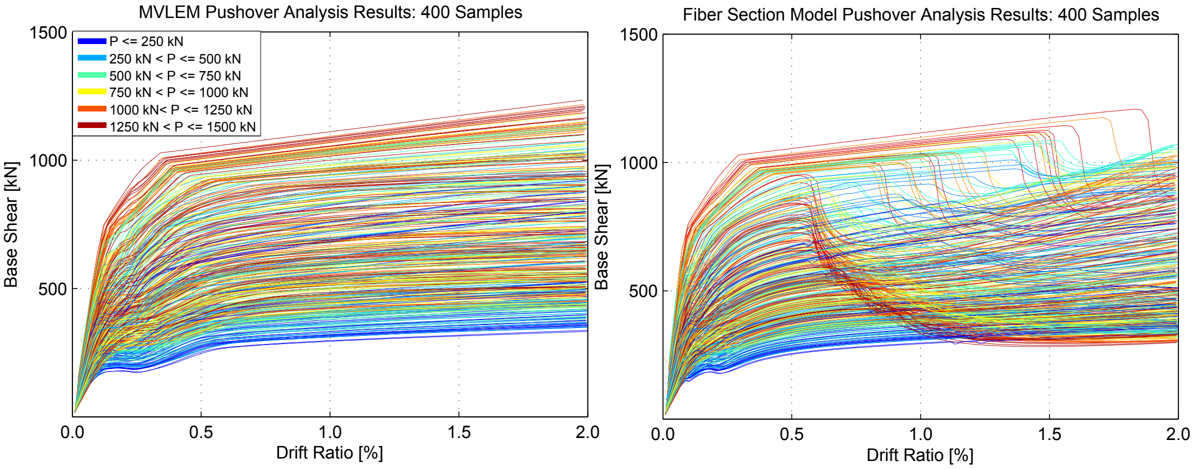

Figure 8: Pushover curves of the studied models

To further investigate the reason for the unlike failure of the fiber section model the contribution of the shear and flexural deformations to the total top displacement was studied. Figures 9 and 10 compare the shear and flexure-induced top displacements of the two models at the last step of the pushover analysis with regard to the wall height and the axial load value. According to Figure 9, shear deformations predicted by the MVLEM are at least two times those predicted by the fiber section model. Under larger axial loads the difference between the estimated shear deformations by the two models becomes even more than a factor of two. In addition, in the case of highly vertically loaded walls with aspect ratios close to 1.5 contribution of the shear deformations to the total top displacement in the MVLEM can be dramatically more than that of the fiber section model. In contrast, the flexural deformations in the MVLEM account for an ignorable portion of the top displacement in the same range (see Figure 10). It can be concluded that for the walls with aspect ratios close to 1.5 which are bearing large axial loads the fiber section model significantly overestimates the contribution of the flexural deformations to the top displacement on one hand and underestimates the contribution of the shear deformations, on the other hand. As a result of noticeable flexural deformations the fiber section model reaches failure at early steps of the pushover analysis. Failure due to shear is not captured in any of the models because no significant strength reduction was considered in the trilinear backbone curve used to define the force-deformation relationship in shear. The above discussion implies that in the studied cases even if both models result in high model qualities in the prediction of the top displacement, they may result in quite different global model qualities when coupled to other partial models which are sensitive to shear deformations.

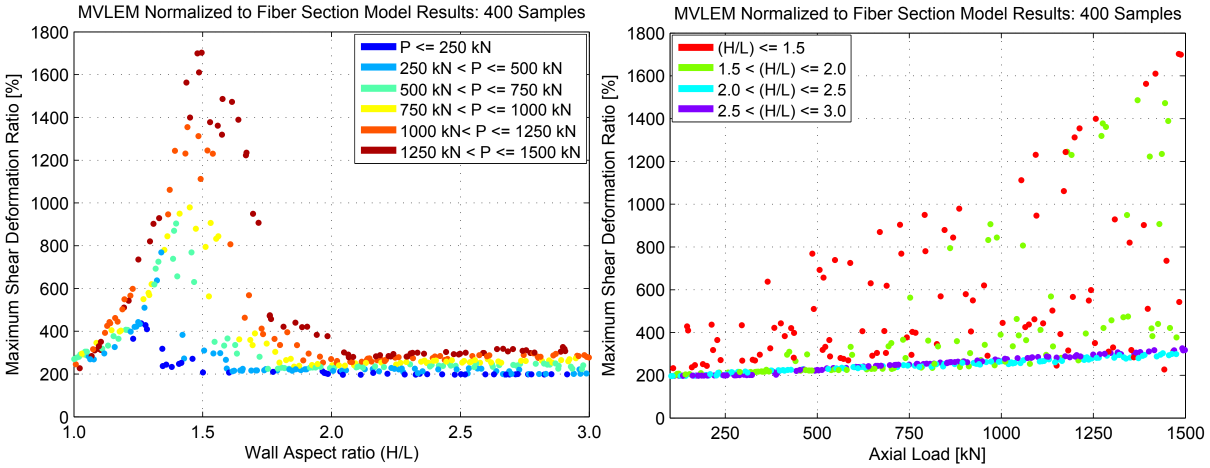

Figure 9: Scatter of the normalized shear-induced top displacement of the studied samples with regard to the variables

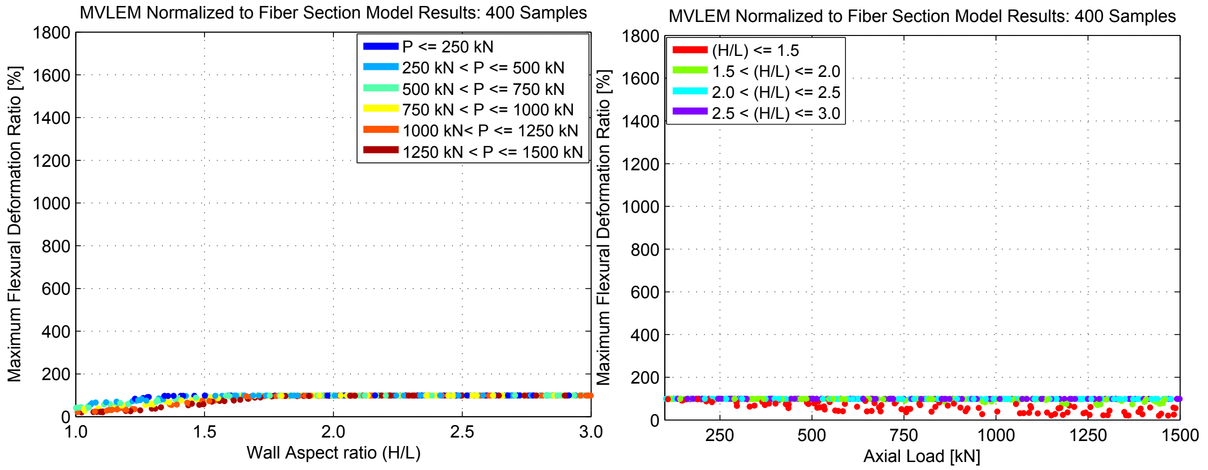

Figure 10: Scatter of the normalized flexure-induced top displacement of the studied samples with regard to the variables

4.2 Dynamic Analysis

44 ground motions were selected according to the far-field record set of FEMAp695 [2] to perform the dynamic analysis. The record set includes twenty-two records (44 individual components) taken from the PEER NGA database. Details about the ground motions can be found in [2]. In sum, 100 samples were chosen which implies a total 440 number of nonlinear dynamic analysis. As in the case of the pushover analysis, each model was imposed to the sampled axial load before the dynamic analysis was performed. The fundamental periods of the models were then computed and used to calculate the spectral accelerations of the models for

each of the 44 selected ground motions. Scatter of the MVLEM fundamental period normalized to that of the fiber section model with regard to the wall height and the axial load value is shown in Figure 11. Clearly, the two models produce almost the same fundamental periods. Only in the range of lower wall aspect ratios the MVLEM estimates the period slightly larger than the fiber section model. The resulting spectral accelerations are also compared for the two models in Figure 12. According to the figure, the most scatter comes from the samples with lower aspect ratios and higher axial loads. As in the case of the pushover analysis, the two models tend to behave differently in this range of the variables due to unlike contribution of the shear deformations to the overall response. The two models were then subjected to the 44 selected ground motions to further compare the dynamic analysis results. Figure 13 depicts the scatter of the resulting maximum top displacement of the MVLEM normalized to that of the fiber section model with respect to the studied variables. Again, the low aspect ratio region accounts for the most differences between the two models' responses. The larger scatter however comes from larger axial load values.

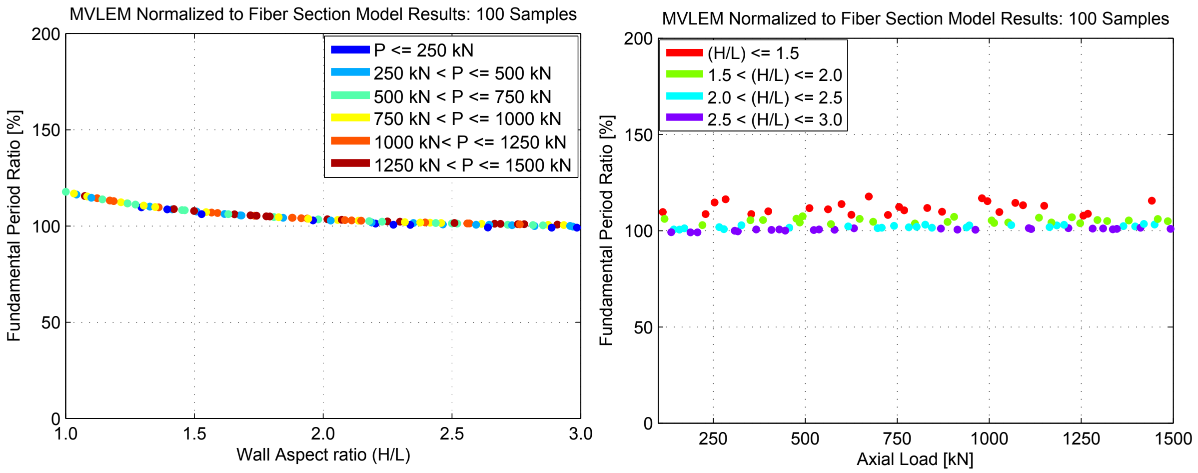

Figure 11: Scatter of the normalized fundamental period of the studied samples with regard to the variables

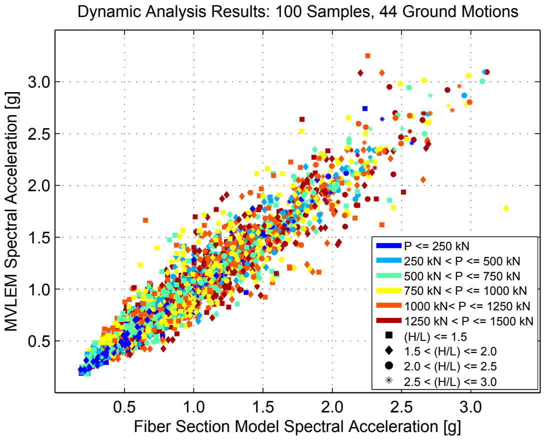

Figure 12: Spectral acceleration at the fundamental period of the studied samples for 44 ground motions

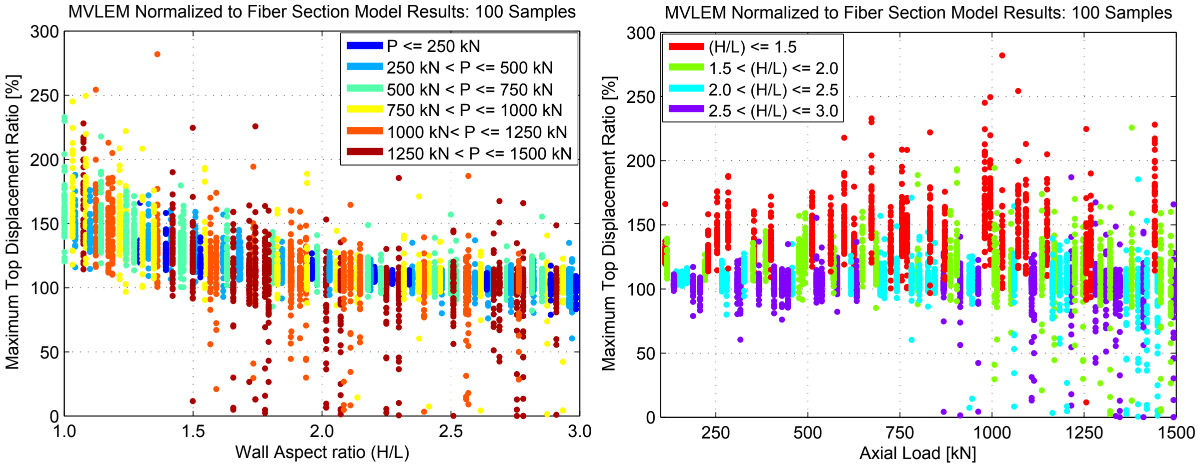

Figure 13: Scatter of the normalized maximum top displacement of the studied samples with regard to the variables

5 CONCLUSIONS

In order to take the first step in the model quality evaluation of coupled frame-wall systems, the main partial model of the system i.e. the wall element was studied through nonlinear static and dynamic analysis. Fiber section model and the Multiple-Vertical-Line-Element-Model (MVLEM) were selected from two major modeling categories (micro- and macro-modeling approaches respectively). To check the potential of the models in the prediction of the wall response, comparison to a selected observed response was made. The models produced responses in close agreement with the observed behavior. Later, the influence of the wall aspect ratio (H/L) and the axial load on the response of the models was investigated through sensitivity analysis. In case of the pushover analysis, the models resulted in quite similar behavior for high aspect ratio walls under low axial loads. However, a dramatic difference was seen between the model responses in the range of low aspect ratio walls under high levels of axial load due to the unlike contribution of the shear deformations to the total top displacement. In the aforementioned range of the variables, the fiber section reached flexural failure at early steps of the pushover analysis since the flexural deformations had to increase significantly in order to fill in for the less contribution of the shear deformations to the top displacement. In the studied cases, this implies that careful attention should be paid to the model quality evaluation of the wall models specifically when they are supposed to be coupled to other partial models. Other partial models may include a moment frame or a soil-footing substructure which their response can be sensitive to shear deformations. If this is the case then even a high quality wall model would not result in a high quality coupled system since it fails to interact properly with the rest of the system. Based on the above discussion, one may be able to define coupling capabilities as one of the properties of a given model. Finally, the dynamic analysis results were presented and compared. According to the results, as in the case of the pushover analysis the most differences between the models' responses is concentrated in the range of low aspect ratios and large axial loads. Further check of the model responses with other models (numerical and physical) is required in order to infer conclusions about the quality of the models. This is the focus of an ongoing research by the first author.

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