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SIMPLIFIED MECHANICS-BASED WOOD FRAME SHEAR WALL MODEL

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SUMMARY

The seismic response of wood frame shear walls is often governed by the hysteresis characteristics of the panel to stud connections. Typically reversed-cyclic tests are performed on shear walls and/or connections to allow the development and fitting of empirical based hysteresis models. The resulting models are therefore loading protocol dependent. Mechanics-based models have the advantage of being independent of the reversed-cyclic protocols. However these models need significant computational time; therefore, the computational efficiency of using such models to generate dynamic response of wood frame shear walls is a bottleneck for seismic reliability analysis.

There are many similarities between the shapes of the load deformation curve of individual nail connectors and that of shear walls. This leads to the possibility of representing a shear wall with a mechanics-based "analog" consisting of a single pseudo "nail". This paper describes the development and verification of such a model. The program input requires a load deformation response from a half cycle static load. The maximum displacement of the loading should exceed the post peak displacement at 80 % of the maximal load. Two applications of the model were considered: wood frame walls with normal and large sheathing panels. Comparisons of model predictions with cyclic and dynamic test results show reasonable accuracy.

INTRODUCTION

Wood shear wall is the primary component in residential and low-rise commercial buildings. In past earthquakes such buildings performed relatively well from the life safety perspective. However, properties losses from the January 17, 1994 Northridge Earthquake in the Los Angles metropolitan region can be predominately attributed to the damages in wood-frame housing where over 50% of the $40 billion damage in properties and approximately 48,000 uninhabitable buildings were experienced. Shear wall dynamic model with enough accuracy and acceptable speed is needed to study the reliability and performance of wood frame building.

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Traditional hysteresis models use single degree-of-freedom (SDOF) nonlinear system to simulate the pinching effect of shear walls [1, 2, 3, 4, 5, 6]. The nonlinear behaviour of these models was exhibited through different definitions of loading and unloading stiffness developed through empirical methods from reversed-cyclic tests of shear walls.

Another kind of model uses multiple degree-of-freedom systems to describe the behaviour of shear walls. Dolan [7] and Foschi [8] used finite element method (FEM) to model the shear wall behaviour under dynamic loading. Filiatrault [9] and Dinehart et al [10] used multiple degree-of-freedom systems to simulate the load displacement behaviour of shear walls. Tarabia and Itani [11] and He [12] tried to develop three-dimensional models for wood frame structures. Common to these models are nail connection tests needed to establish the model parameters.

Many SDOF models were developed from reversed-cyclic tests and their accuracy depends on the loading protocol. FEM based mechanical models generally need significant computational time and represent a bottleneck to generate dynamic response of the wood shear walls for reliability analysis. This paper describes a SDOF model in which the characteristic load displacement curve of shear walls is simulated with a large pseudo nail. With this model, the dynamic response of shear walls can be calculated efficiently compared with detailed FEM models.

MODEL DEVELOPMENT

There are many similarities between the shapes of the load deformation curve of individual nail connectors and that of shear walls (Figure 1, Figure 2). In both figures, the initial load-displacement relationship is approximately linear. With the increasing of displacement, nonlinearity becomes apparent. After reaching the ultimate or peak load, the load decreases when displacement continues to increase. The basic shape of pushover test curves of nails and shear walls are upwardly convex. The scales are obviously different between the two curves. Furthermore, connection load displacement curves show higher variability compared to the wall load displacement curves.

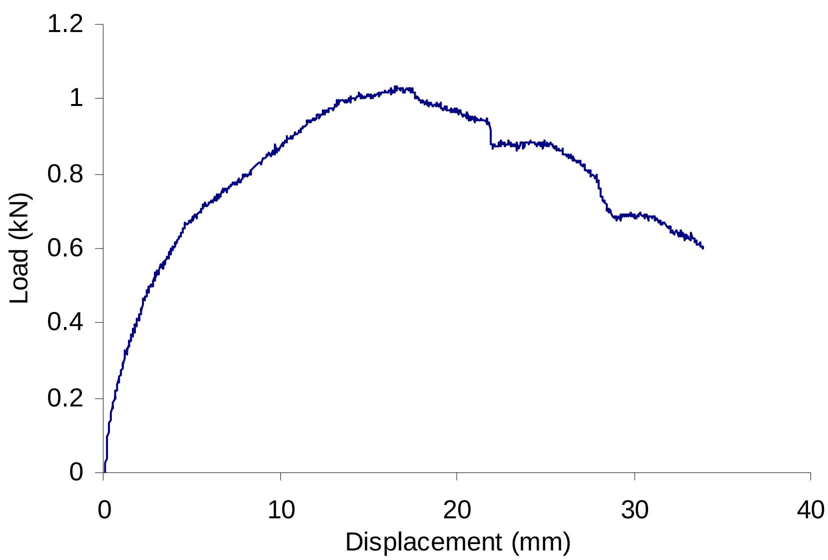

Figure 1 Load displacement relationship from a nail connection test

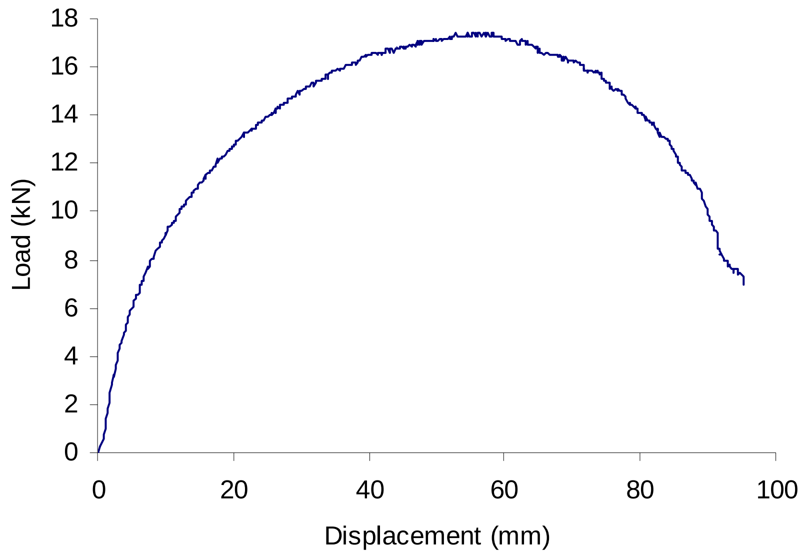

Figure 2 Load displacement relationship from pushover test of a shear wall

The similarities can be explained by the mechanism of wood frame shear wall. It is well recognized that the lateral response of shear walls is governed by the characteristics of the panel to stud connections. When a shear wall is deformed, each nail experiences some deformation. The effect of the deformation from all nails is superimposed together to exhibit an overall load displacement curve for the shear wall.

Since the load-displacement curve of the shear wall is a group effect from all of the nail connectors and its shape is similar to that of the nail connectors, it is possible to represent the shear wall with a single pseudo nail model (Figure 3). In this paper, a mechanics based nail model [13] is chosen as the representing analog. This nail model used finite element method to describe the nonlinear behaviour of the elasto-plastic properties of the nail, the nonlinear interaction between nail and surrounding wood medium and formation of gap (required for the response during load reversal). The reaction of surrounding wood medium is assumed to be a function p(w), as shown in Figure 4. The embedding function has six parameters, Q_0, Q_1, Q_2, Q_3, K and D_{max}.

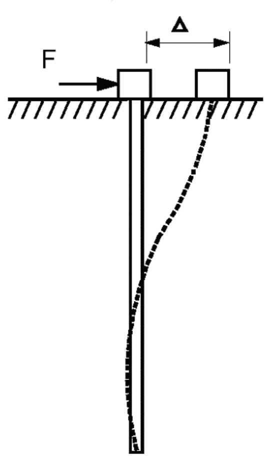

Figure 3 Nail connector model [13]

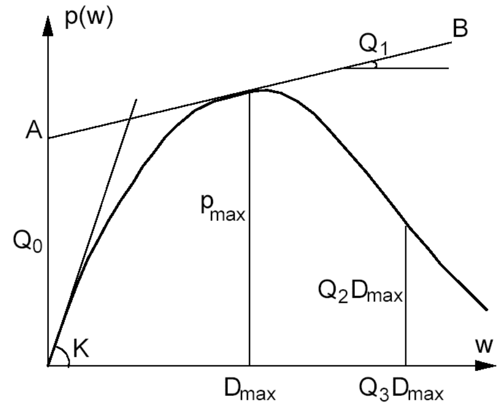

Figure 4 Embedment function of p(w) [13]

This pseudo nail model is a SDOF system from which the hysteresis force is calculated with a multiple degree-of-freedom finite element program, HYST [13]. Since the pseudo nail does not have physical dimensions, additional two parameters are required: length of the nail (L) and diameter of the nail (D_i). To simplify the problem, Q_2 is set to 0.8. In total, there are seven parameters: Q_0, Q_1, Q_3, K, D_{max}, L and D_i, to be determined in order to simulate a shear wall.

Finding the best parameters of the simulating nail model leads to an inverse problem which generally has multiple solutions. An optimization function can be written to minimize the summation of squared error, shown as:

$$\min \varepsilon = \sum_{i=1}^{N} (F_{i,test} - F_{i,\mathrm{model}})^2$$

where
I = the i^{th} discrete point;
$F_{i,test}$ = value of force from tests at the i^{th} point;
$F_{i,model}$ = value of force calculated from models at the i^{th} point.

This optimization is subjected to variables of Q_0, Q_1, K, Q_3, D_{max}, L and D_i. These variables can be identified with different search methods.

To capture the characteristics of loading and unloading paths, the program input of this model requires a half cycle static load. The peak displacement of the loading should be more than the displacement at ultimate load. A post peak load of 80% maximal load is recommended here.

SEARCH METHODS

Hill-climbing method

Foschi [13] developed a program of hill-climbing to find the parameters of his nail model from connector test results. This method repeats one step forward or backward for each variable and then compares the results to find the best step for the next solution. A good initial solution is important because the method converges to a local optimum. This study modified Foschi's program for the optimization problem with seven parameters.

Random search method
A random search program was written by Foschi to identify the parameters of the nail model [13]. This program generates all trial solutions within upper and lower boundaries randomly. Subsequent trials are limited to a given distance from current best solution. If a trial is better, it updates the best solution. Otherwise, it continues to search for a better solution.

Simplex method
Simplex method [14] was reported to succeed in identifying the parameters of a modified BWBN model [15]. This method uses reflection, contraction and expansion to find better solutions. An open-source FORTRAN subroutine [16] is used in this study to identify the parameters.

Genetic algorithm
Genetic algorithm (GA) succeeded in identifying the parameters of BWBN model [17]. This algorithm simulates the evolution of nature in order to find the best solution. Typical operations of this method include crossover, mutation and roulette wheel selection. Encoding and decoding for binary operation are needed before and after other operations. This study uses an open-source FORTRAN program [18] as a subroutine of optimization.

Neural network
All methods discussed above have to run repeatedly in order to get the final solution. The intermediate calculation results may imply some useful information. Artificial neural network (ANN) is applied to utilize this information. A multilayer perception, trained by back propagation (BP) algorithm, is used here. The input of neural network has five parameters, Q'_0, Q'_1, Q'_3, K' and D'_{max}, which express the shape of the load displacement curve from shear wall experimental results. The geometrical meaning of these five variables is the same as that of the embedding function (Figure 4). The output has seven parameters to be optimized, which are variables of embedding function of p(w). Training method is Levenberg-Marquardt algorithm. Since neural network blindly predicts the parameters from existing solutions and their errors, its real predicted error has to be re-calculated outside the network.

MODEL VERIFICATION

The pseudo nail model is compared with experimental results of full size shear walls under cyclic and dynamic loads [19, 20]. The 2.4x2.4 m shear walls used No. 2 and better 38x89 mm Spruce-Pine-Fir dimensional lumber. The end studs and top plates were double members and the bottom plates and interior studs were single members. The sheathing panels were 9.5 mm-thick oriented strand board panel connected to the framing members with pneumatically driven 50 mm spiral nails. The two panel configurations are (1) one 2.4x1.2 m panel horizontally oriented at the bottom and two 1.2x1.2 m panels at the top (Test 8 and 11of Durham [19]), and (2) one 2.4x2.4 m panel (Test 6 and 10a of Durham [19]). Interior nail spacing for all walls is 300mm. The edge nail spacing is 150 mm for panel configuration 1 and 75 mm for panel configuration 2, respectively. Hold downs were used to prevent the overturning of the wall. The dynamic experimental results were processed with a low-pass filter in frequency domain.

Example 1
One example is the wall sheathed with a normal size panel (Configuration 1). The unloading part of the input curve was estimated from the cyclic test results, shown in Figure 5. The fit resulting from different optimization methods are shown in the same figure. The obtained parameters are shown in **Table 1**. The results under reversed-cyclic loading are shown in Figure 6. The comparison under dynamic loading is shown in Figure 7. The visco-damping ratio in dynamic calculation is 1% of the critical damping in respect to the initial tangential stiffness. The calculated response curve in Figure 7 is phase shifted by

0.09 seconds to match the measured response. This figure is truncated along the abscissa to show only the significant portion of the results.

Table 1 Parameters for the Configuration 1 shear wall

	Q_0 (kN/mm)	Q_1 (kN/mm^2)	K (kN/mm^2)	D_{max} (mm)	Q_3	D_i (mm)	L (mm)
Hill-climbing	0.7389	0.05830	0.2866	30.606	1.3677	9.6000	135.00
Random	0.0807	0.05113	0.1908	27.697	1.7772	11.605	264.61
Simplex	0.7707	0.02781	0.1100	38.652	1.1867	11.122	455.64
Genetic algorithm	0.0491	0.09211	0.1903	28.093	1.3583	9.8225	397.52
ANN-BP	0.4847	0.05980	0.2456	30.017	0.3836	10.244	130.88

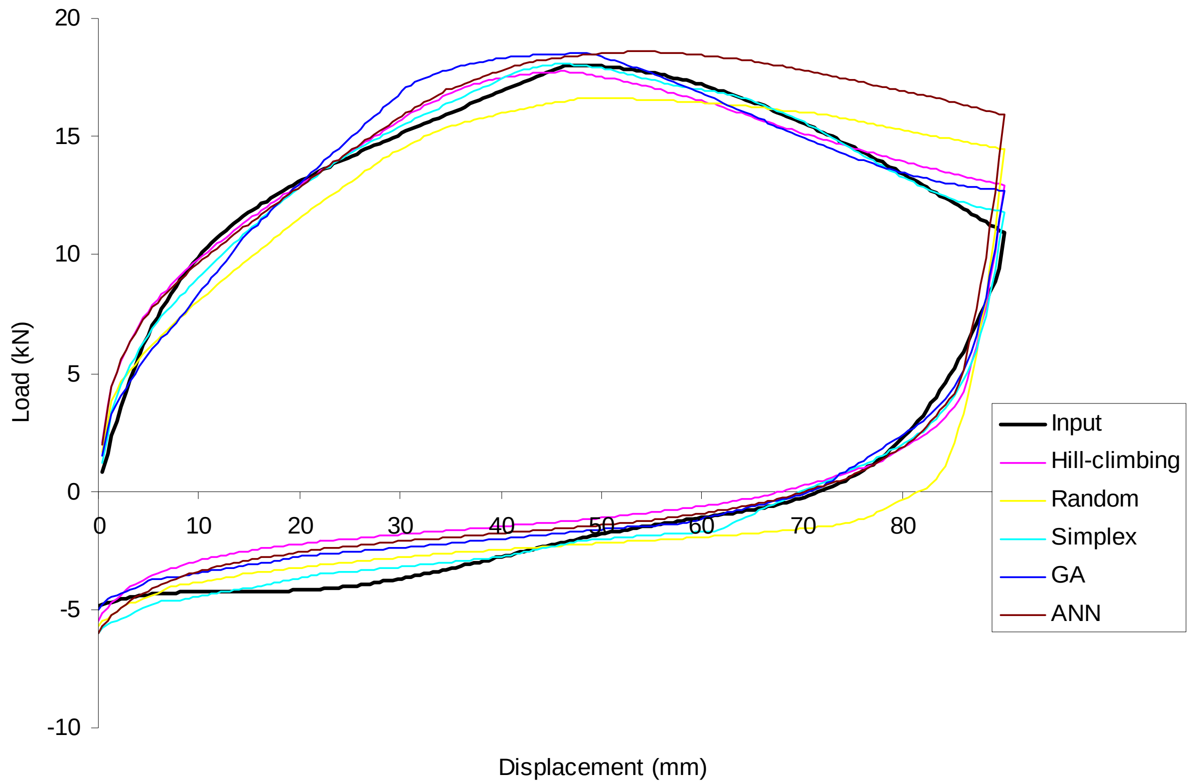

Figure 5 Input of the optimization for Configuration 1 and its results

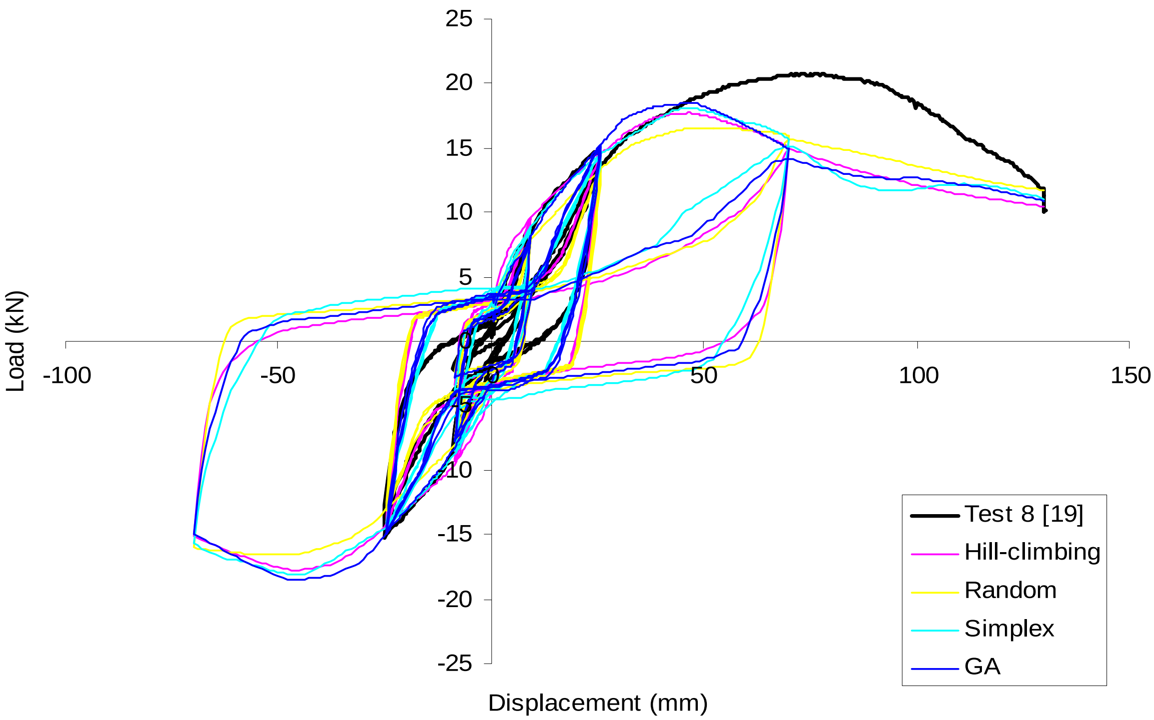

Figure 6 Comparison of predicted and test results of Configuration 1 under cyclic load

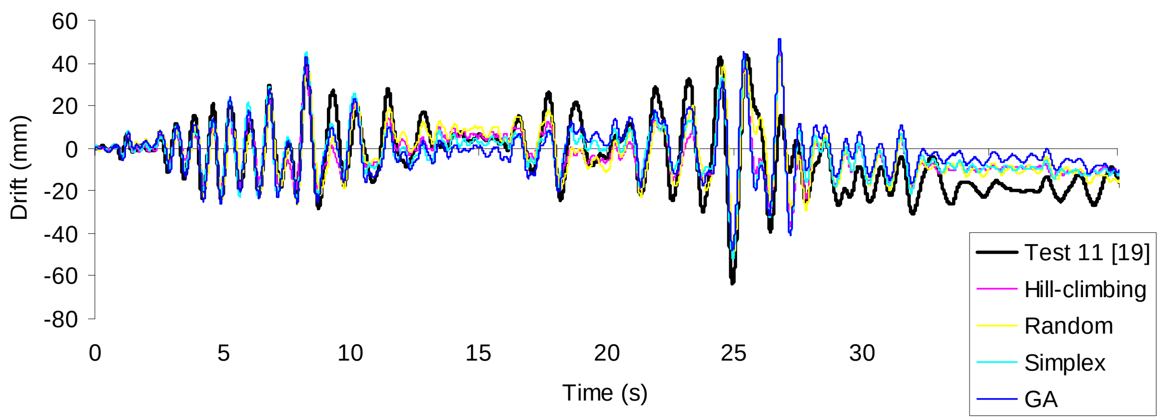

Figure 7 Comparison of predicted and test results of Configuration 1 under dynamic load

Example 2

Another example is the wall sheathed with oversized panels (Configuration 2). The input curve was obtained through LightFrame3D (Figure 9.18 of He [12]), shown in Figure 8. This figure also shows the results of the model obtained with different methods. The parameters used in the model are shown in **Table 2**. The comparison between experimental and calculated results under reversed-cyclic loading is shown in Figure 9. The comparison under dynamic loading is shown in Figure 10. The damping ratio is same with that in Example 1. The calculated dynamic response curve is flipped and phase shifted with

0.28 seconds in order to fit the experimental results. This figure is truncated along the abscissa to show only the significant portion of the results.

Table 2 Parameters for the Configuration 2 shear wall

	Q_0 (kN/mm)	Q_1 (kN/mm^2)	K (kN/mm^2)	D_{max} (mm)	Q_3	D_i (mm)	L (mm)
Hill-climbing	8.6214	0.02924	0.1733	32.216	1.438	12.131	412.23
Random	8.2248	0.03400	0.2191	25.211	1.963	11.627	463.87
Simplex	4.8978	0.00977	0.1926	44.537	0.835	12.988	55.84
Genetic algorithm	4.1853	0.04481	0.2582	32.741	1.469	11.513	313.46

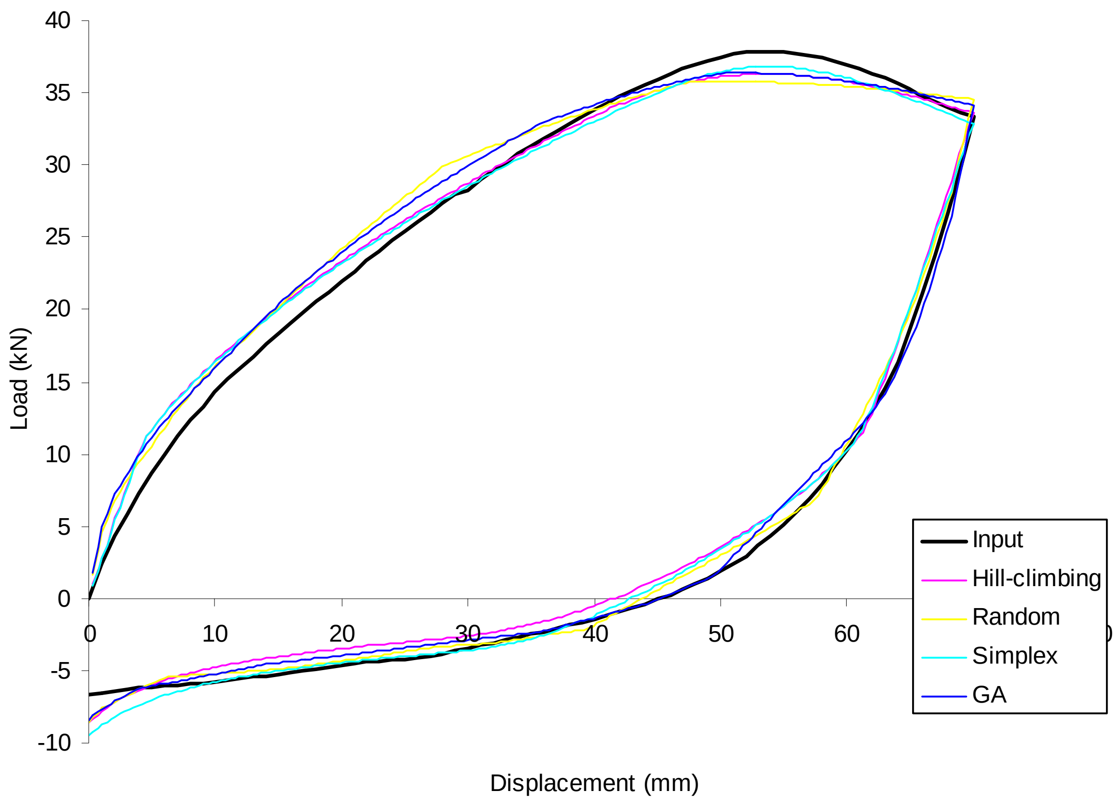

Figure 8 Input of the optimization for Configuration 2 and its results

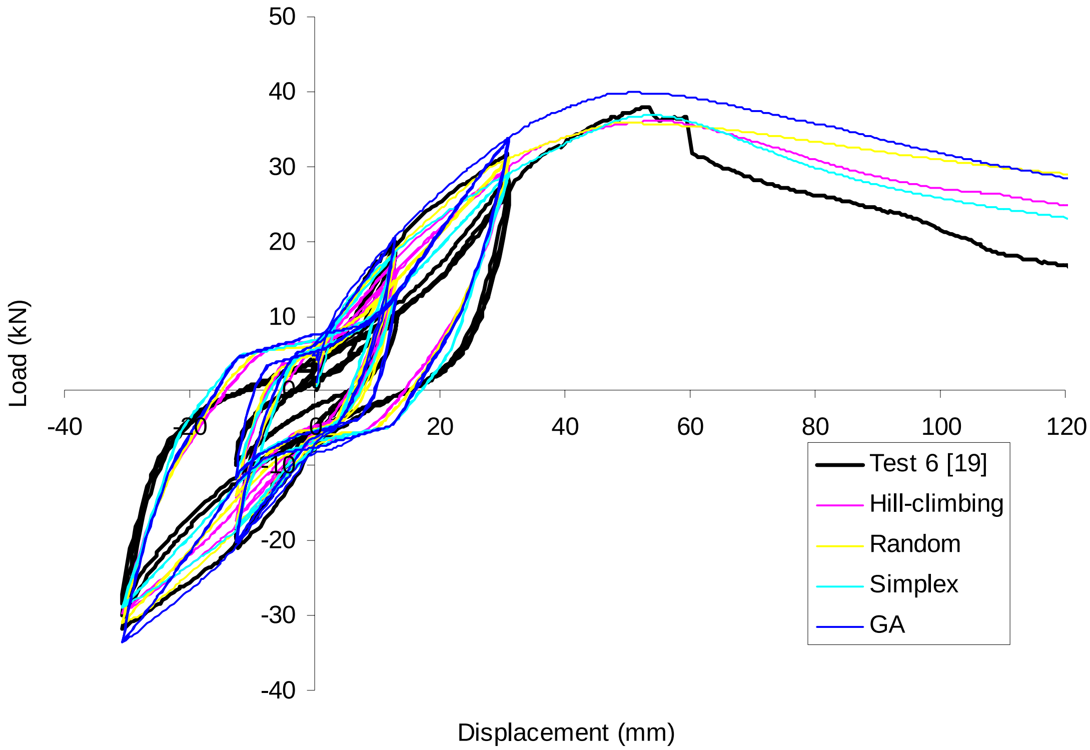

Figure 9 Comparison of predicted and test results of Configuration 2 under cyclic load

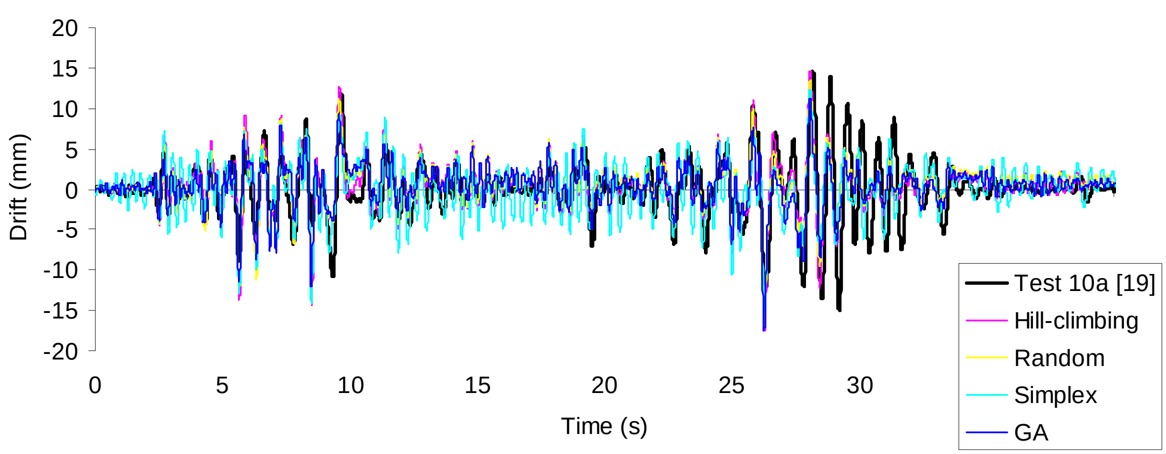

Figure 10 Comparison of predicted and test results of Configuration 2 under dynamic load

For artificial neural network, the minimal number of layers and neurons are determined by the type and number of training data. Generally, its results have a relatively large error compared with other methods. The best results from neural network are shown in Figure 5. Even in the best case, the results are worse than the best solution in the training data. This is understandable since neural network does not evaluate the function value after prediction.

For all other methods, the accuracy and convergence speed of optimization are heavily dependent on the initial values or boundaries and the problem itself. Hill-climbing and simplex method need a fairly good estimation of initial values while random and genetic algorithm have to be given a range of upper and lower boundaries.

The comparison from Example 2 reveals that all methods give relatively good results (Figure 8, Figure 9, Figure 10). But the parameters in **Table 2** show that simplex method apparently converges to a different solution. This phenomenon reveals that there are multiple sets of solutions for this optimization problem. For the fitting model, it is not a problem since all of these solutions give similar results. However, it will affect the results from dynamic calculations because different sets of solutions may need different damping coefficients which would be determined from empirical trials in the program. Figure 9 shows that the simplex method significantly overestimates the drift, which indicates that the damping coefficient may be different for this set of solutions.

CONCLUSIONS

A pseudo nail model is developed to simulate the behaviour of shear walls. The model is a SDOF system with the hysteresis force calculated using a finite element program. This model is much faster to calculate the dynamic behaviour than with mechanism based FEM shear wall models.

The input of this model is a half cycle of load displacement curve, which can be obtained from either static test results or other mechanics based finite element programs. Parameters of the model are identified with different search methods, including hill-climbing method, random search method, simplex and genetic algorithm. The results from these search methods are compared well with the results from reversed-cyclic tests and dynamic tests.

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