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Benefits of Using Optimization Methods in Structural Engineering Practice: Case Studies

Bulent N. Alemdar[1], Sudip Chakraborty[2], Pratik Deb[3], Zheng Wu[4]

[1] Bentley Systems, Inc., Carlsbad, CA, USA, bulent.alemdar@bentley.com
[2] Bentley Systems, Inc., Yorba Linda, CA, USA, sudip.chakraborty@bentley.com
[3] Bentley Systems, Inc., Yorba Linda, CA, USA, pratik.deb@bentley.com
[4] Bentley Systems, Inc., Watertown, CT, USA, zheng.wu@bentley.com

1. Abstract
An optimal design solution is a very challenging task to achieve in structural engineering. It is often a rigorous iterative process to produce the best solution in terms of the prescribed engineering criteria or objective while satisfying the design constraints. In recent years, optimization software tools are utilized in many diverse areas of structural engineering. Even though the benefits of optimization tools are well recognized, these tools are not efficiently integrated into practicing engineer's design workflow.
This paper intends to show benefits of using an optimization software tool integrated with an analysis tool. Two examples are selected to serve this purpose. The first example deals with period optimization of a braced moment resisting frames. This is accomplished by finding optimum configuration of braces so that minimum structural period is obtained. The second example addresses a two-span concrete bridge supplemented with a base-isolator, in which optimal choices of the base-isolator properties plays a significant role in mitigating bridge damages. In this work, a nonlinear dynamic analysis is conducted for a selected range of different ground motion histories and it is aimed to find optimal isolator properties to keep bridge damages at minimum.
In the paper, two software packages including a finite element analysis library and an optimization library are coupled together to find optimum solutions for the aforementioned examples. Both software packages are stand-alone libraries. In other words, they are not developed for any specific domain. This level of separation provides a great flexibility to apply them to a broad range of engineering problems. The optimization package is developed as a general tool for rapid implementation of optimization applications. The finite element analysis software is developed for nonlinear static\dynamic analysis of any type of structures. To demonstrate the benefits of these two packages, they are integrated into the solution framework enabling design engineers to achieve the improved design solutions. It is intended to show that optimization and structural analysis tools can be effectively used together to provide supplemental design information for structural engineers.

2. Keywords: period optimization, nonlinear dynamic analysis, seismic isolation, base isolator

3. Introduction
In recent years, optimization software tools are utilized in many diverse areas in structural engineering such as geometry (topology) optimization, structural response optimization and structural cost optimization, to name a few. Even though the benefits of optimization tools are well recognized, these tools are not efficiently integrated into practicing engineer's design workflow. When optimization and analysis tools are effectively used together, they can provide valuable supplemental information during structural design process.
This paper intends to show benefits of using an optimization software tool integrated with an analysis tool to investigate optimum structural response for a few selected examples. This objective is accomplished by first creating a computer software solution framework in which two independently developed software libraries are combined: Darwin Optimization Framework [1] and Nonlinear Finite Element Analysis Library [2].
Two examples are targeted in the present study. The first example deals with period optimization of a steel moment resisting frame. Strengthening existing old structures to control excessive story deformations can be carried out by reinforcing these structures with braces. To this end, this example searches for the optimum configuration of braces to achieve minimum structural period. The second example addresses dynamic response of a two-span concrete bridge supplemented with a base-isolator. Proper choice of the base-isolator properties plays an important role in mitigating damages in the bridge during a ground motion excitation. Hence, optimal base-isolator governing properties are investigated for a broad range of earthquake intensities in this example.
It should be noted that the main focus of the current study is reserved for the examples provided in the paper even though the developed solution platform is the cornerstone of the current effort. This decision is based on the main objective of the paper that it is intended to show benefits of using optimization and analysis tools together to get valuable information for design, rather than providing details of software development or technical details of optimization and analysis tools.

3.1 Darwin Optimization Framework

Darwin Optimization Framework is designed and developed as a general tool for rapid implementation of any optimization application. It encapsulates the competent genetic algorithm library for single and multiobjective optimization, parallel computing/evaluating possible solutions, linear and nonlinear constraint handling methods. It allows parallel optimization on a single many-core machine or a cluster of many-core machines. The library can address single and multi-objective optimization problems with linear, nonlinear, inequity and equity constraints.

In general, solving an optimization problem requires searching for a set of optimal or near-optimal values of decision variables to minimize and/or maximize the predefined objective function(s) while meeting the constraints. During the optimization process, each decision variable is taking the values within its prescribed range with specified increment, and the objective function (or multiple objective functions) and constraint functions are evaluated for each possible solution.

The optimization framework is developed as an effective and scalable tool to solve highly generalized optimization problems with Genetic Algorithm (GA). It has the following features including:

- Solve for linear and nonlinear optimization problems
- Handle linear, nonlinear equality and inequality constraints
- Solve Single and multiple objective optimization problems
- Enable parallel optimization on a single many-core machine and a cluster of many-core machines
- Offer dynamic runtime of optimization convergence rate for both single and multi objective optimization runs

3.2 Nonlinear Finite Element Analysis Library

The analysis library is developed as a general finite element analysis tool that targets rapid and easy integration with any structural analysis program. It is an object-oriented software framework. It is a COM based DLL that provides a very rich API addressing a broad range of structural analysis features. The library includes a collection of linear\nonlinear finite elements and offers several different solution procedures for linear\nonlinear static and dynamic analysis.

4. Case Studies

4.1. Case Study 1: Structural Period Optimization for a Braced Moment Frame

The model definition is given in Fig. 1. W250x67 (W10x45) shape is chosen for all elements and modulus of elastic (E) is 200000 MPa (29000 ksi). A nodal mass with a value of 57.02 kN-s2/m (1 kip-s2/in) is defined at each node in horizontal direction only. With this setup, the structural period is calculated as T=6.24 seconds.

In order to strengthen the system and to reduce the structural period, a total of five braces (Area = 645.16 mm^2 or 10 in^2) is introduced to the structure, assuming that each bay can accommodate only one brace. Figure 2 shows a few possible configurations and corresponding structural periods. It should be acknowledged that it is not practical to run all possible configurations (i.e., 2^{10} possible solutions) to find an optimal configuration with minimum structural period. Instead, the proposed solution has a great potential to find optimal solution while keeping numerical computation at minimum. Figure 4 shows a snapshot of the optimization framework that is run in its own GUI. The optimal configuration is shown in Fig. 3 in which the period is calculated as T=1.91 seconds for the shown configuration.

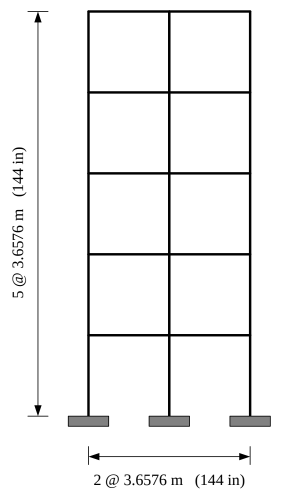


Figure 1: Unbraced Frame (T=6.24 s)

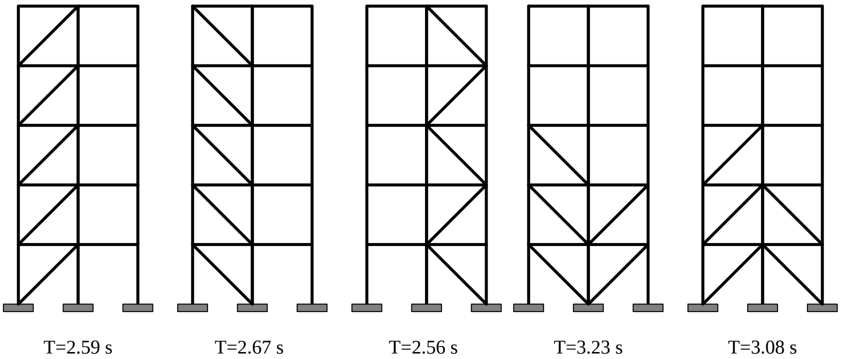


Figure 2: Several Alternative Braced Frame Solutions

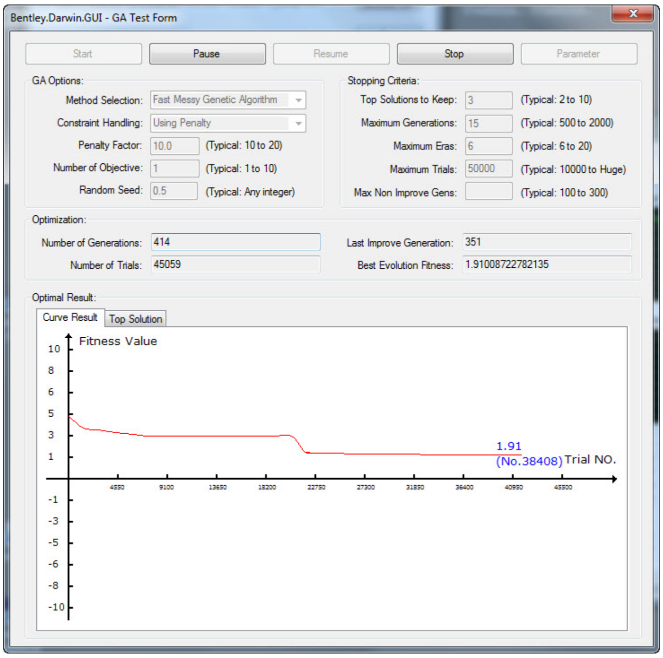


Figure 3: Darwin Optimization GUI run for Case Study 1

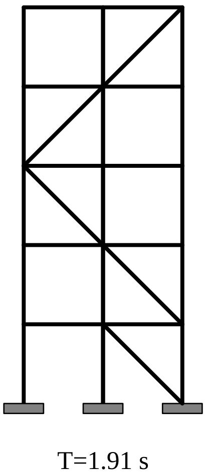
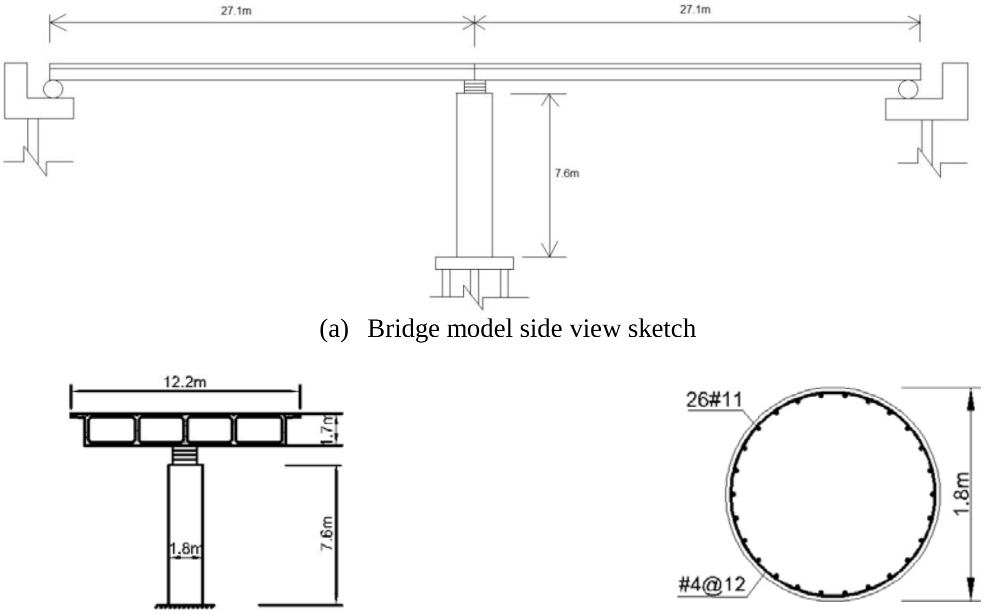


Figure 4: Optimal Braced Frame Configuration

4.2. Case Study 2: Optimal Base-Isolator Properties Selection

In this study, a two-span concrete bridge supplemented by a base-isolator is addressed and optimum base-isolator properties are investigated for best seismic performance under earthquake ground motions. The bridge model geometry and cross-section properties of pier column are defined in Fig 5. The material values are the same as those used in the study of Zhang and Huo [3]. The calculated deck mass is 340.0 tons for each span and the column mass is 44.0 tons. A base-isolator is placed between the pier column top and girder.

A nonlinear time history analyses is carried out to evaluate the seismic performance of the bridge. The seismic loading is applied only in the longitudinal direction, i.e. in the plane of Fig. 5a. The seismic response in transverse direction is ignored. A total of 50 ground motions are selected from PEER Strong Motion Database [4]. The selection intends to uniformly distribute peak ground acceleration (PGA) from 0.05g to 1.5g.



(a) Bridge model side view sketch

(b) Bent and deck sketch (c) Column cross section

Figure 5: Model Definition for Case Study 2

The bridge girder is assumed to be elastic. Similarly, the reinforced concrete column remains elastic except that its characteristic nonlinear response is represented only with a rigid-plastic hinge spring inserted at the column's base. The spring is assumed to have an infinite initial stiffness before yielding. A pushover analysis with a fiber cross-section idealization is carried for the column to obtain nonlinear properties of the plastic hinge spring. This study yields the following results: $M_{y,hinge}$ = 7800.0 kN·m, $\theta_{y,hinge}$=0.00427 rad, and $K_{y,hinge}$=4.7×10^4 kN·m/rad.

The isolator element is formulated based on an evolution equation given by Park et al.[5]. The force-displacement relationship of the two transverse directions is coupled:

$$F_2 = \alpha_2 K_2 u_2 + (1 - \alpha_2) F_{y2} Z_2 \quad (1a)$$

$$F_3 = \alpha_3 K_3 u_3 + (1 - \alpha_3) F_{y3} Z_3 \quad (1b)$$

where F_i, u_i, K_i, F_{yi} and α_i are the shearing force, deformation, initial stiffness, yielding force and post-yielding stiffness ratio, respectively and $i = 2, 3$. The terms Z_2 and Z_3 are referred to as evolutionary variables and they represent hysteretic components of the restoring forces. These terms are dimensionless and defined in the following ordinary different equations (ODE):

$$\begin{Bmatrix} \dot{\mathrm{Z}}_2 D_{y2} \\ \dot{\mathrm{Z}}_3 D_{y3} \end{Bmatrix} = \begin{bmatrix} \mathrm{A} - \mathrm{Z}_2^2[\gamma \mathrm{sign}(\dot{u}_2 Z_2) + \beta] & -\mathrm{Z}_2\mathrm{Z}_3[\gamma \mathrm{sign}(\dot{u}_3 Z_3) + \beta] \\ -\mathrm{Z}_2\mathrm{Z}_3[\gamma \mathrm{sign}(\dot{u}_2 Z_2) + \beta] & \mathrm{A} - \mathrm{Z}_3^2[\gamma \mathrm{sign}(\dot{u}_3 Z_3) + \beta] \end{bmatrix} \begin{Bmatrix} \dot{u}_2 \\ \dot{u}_3 \end{Bmatrix} \quad (2)$$

in which D_{y2} and D_{y3} are the yielding displacements, respectively. The constants A, β and γ are controlling constants and they define the shape of hysteresis loop. In this study, these constants are chosen as follows: $\mathrm{A} = 1.0$, $\beta = 0.1$ and $\gamma = 0.9$. It should be mentioned that even though the isolator element is developed for general 3D analysis, this study utilizes only a 2D response of the isolator.

For the isolator element, the following three parameters dominantly govern its response: initial stiffness (K_0), yielding strength (F_y) and post-yielding stiffness ratio (α). For a certain type isolator, the post-stiffness ratio is usually fixed in a certain range. For example, it is typically chosen between 1/5 - 1/15 for an elastomeric rubber bearing (ERB), and 1/15 - 1/30 for a lead-plug rubber bearing (LRB), and 1/50 - 1/100 for a friction pendulum system (FPS). In the current study, a constant value of 1/20 is chosen for α, which is a typical choice for a LRB type isolator.

It is essential to find optimal values of K_0 and F_y of the base-isolator for best seismic performance, which are also the chosen optimization decision variables in the present study. Based on the column stiffness and the hinge properties, these parameters are searched in the following ranges:

$$K_0 = [0.2 - 1.2]\, K_{column} \tag{3a}$$

$$F_y = [0.3 - 1.3]\; M_{y,hinge}/H_{column} \tag{3b}$$

in which $K_{column} = 6.2 \times 10^4 \text{kN/m}$ is the elastic stiffness of the pier column under cantilever boundary condition and $H_{column} = 7.6m$ is the column height.

In the current study, a seismic performance is measured in the form of a Damage Measure (DM). This is defined according to the deformations measured in the isolator element and at the column hinge. It is assumed that a smaller number of DM indicates a better seismic performance.

The damage measure in the isolator is defined as follows:

$$DM_{isolator} = \Delta_{isolator}/0.1 \tag{4}$$

where $\Delta_{isolator}$ is the deformation of the isolator. The damage measure for the column hinge is defined according to FEMA356 (FEMA, 2000):

$$DM_{column} = \theta_{hinge}/\theta_{y,hinge} \tag{5}$$

where θ_{hinge} is the column rotation measured in the column hinge.

A global level DM is then defined as a proportional summation of the two component DMs:

$$DM_{global} = 0.40DM_{column} + 0.60DM_{isolator} \tag{6}$$

The weight ratios are chosen based on the consequences of the corresponding component damage. A larger weight value is assigned to $DM_{isolator}$ and this is because a large deformation in the isolator also means extensive deck movement, which could induce other damages such as span collapse, pounding at joints and foundation, and abutment failures.

Finally, the optimization problem is postulated as follows: minimize the bridge system damages by choosing optimal base-isolator properties. Mathematically, it is expressed as follows:

$$\min\left(DM_{global}\right) \tag{7a}$$

while subjected to:

$$K_0 \in [0.2 - 1.2]K_{column} \tag{7b}$$

$$F_y \in [0.3 - 1.3]\, M_{y,hinge}/H_{column} \tag{7c}$$

Optimal seismic isolator parameters (i.e., K_0 and F_y) for each ground motion is searched with the help of the optimization software. More specifically,

For each ground motion, a number of nonlinear time history analysis runs are performed to obtain optimum values of (K_0, F_y) of the base isolator (i.e., the problem postulated in Eq. (7) is iteratively solved). It is observed that almost 500 runs suffice to obtain the optimal values for all ground motions (i.e., 10 iteration for each ground motion observed). The results are portrayed graphically in Figs. 6-8. Figure 6 shows calculated global level damage measures (DM_{global}) obtained with optimum values of (K_0, F_y) for each ground motion. Corresponding optimal values of K_0 and F_y are given in Figs. 7 and 8, respectively. It is interesting to note from the figures that yielding strength (i.e., F_y) is more crucial for seismic damage mitigation than initial stiffness of the isolator.

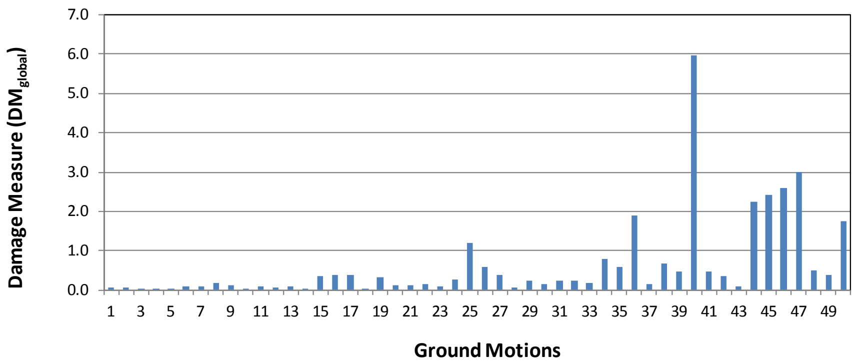


Figure 6: Damage measures with respect to optimal values of K_0 and F_y.

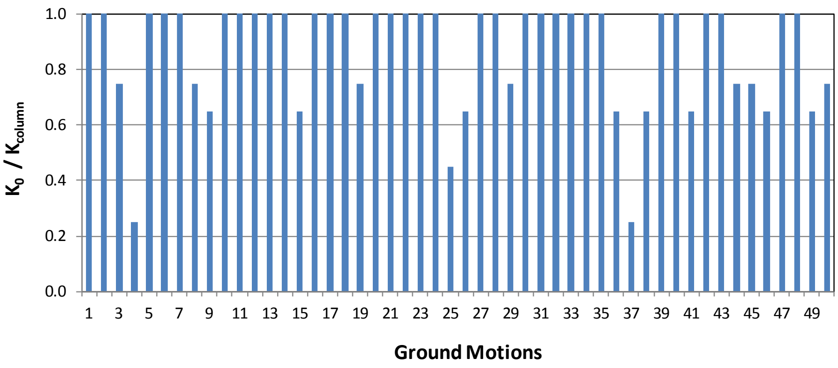


Figure 7: Normalized optimal values of K_0 with minimum DM_{global}.

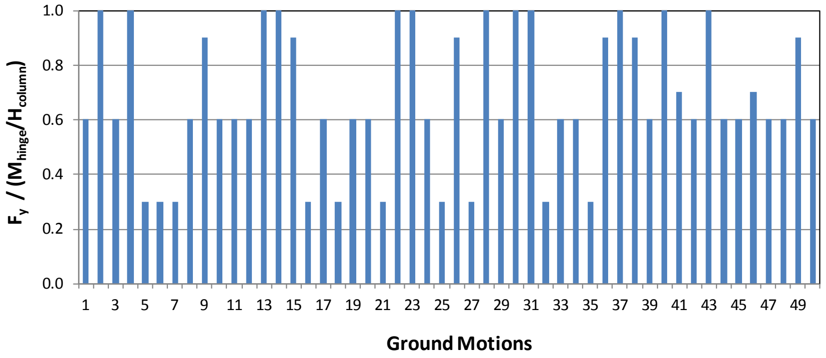
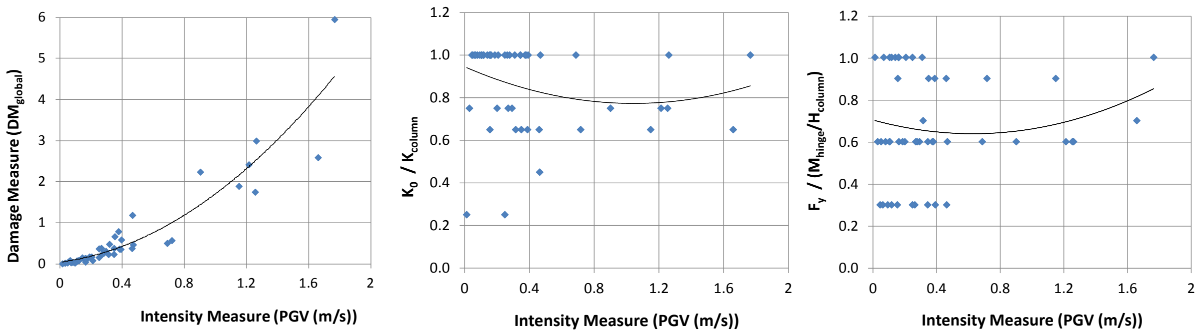


Figure 8: Normalized optimal values of F_y with minimum DM_{global}.

Figure 9a shows DM_{global} with respect to ground motion intensities. A polynomial curve that best fits the data is also shown in the figure. Each mark in the plot indicates a DM_{global} value calculated with respect to a specific ground motion and with the optimal values of K_0 and F_y. A similar exercise is carried out for optimal values of K_0 and F_y, as shown in Figs. 9b and 9c. It is noted from these figures that the optimal ranges for K_0 and F_y are about $0.6K_{column}$ - $1.0K_{column}$ and $0.6M_{hinge}/H_{column}$ - $1.0M_{hinge}/H_{column}$, respectively. The only exception is for the cases recorded with low ground motion intensities.



(a) (b) (c)

Figure 9: Optimal values of DM_{global}, K_0 and F_y for different ground motion intensities.

Table 1 summarizes the optimal configurations which are read directly from the fitting curves in Fig. 9. The table also compares these results to those of Zhang and Huo [3]. The reference utilizes the fragility function method to investigate the optimum base-isolation properties and it applies a more rigorous nonlinear analysis (i.e., a fiber section nonlinear beam element used for bridge piers). The current study shows that the yielding strength of the isolator (F_y) is more influential in controlling damage than the initial stiffness of the isolator (K_0). It is also noted that $F_y = 0.65M_{hinge}/H_{column}$ is an optimal choice for all ground motion histories.

Table 1: Optimal Base-Isolator Values

	At PGV=0.25m/s		At PGV=0.50m/s		At PGV=0.75m/s		At PGV=1.0 m/s	
	Current Study	Ref. [3]	Current Study	Ref. [3]	Current Study	Ref. [3]	Current Study	Ref. [3]
K_0/ K_{column}	0.86	0.85	0.82	0.65	0.78	0.85	0.77	0.75
$F_y/(6M_{hinge}/H_{column})$	0.67	0.55	0.64	0.45	0.64	0.45	0.66	0.65

5. Conclusions

This paper proposed an integrated approach of integrating the well developed two software components including the nonlinear finite element analysis and parallel optimization tools. The optimization tool automatically generates and searches for the better solutions while the finite element analysis solver is employed to evaluate each alternative solution. An integrated approach is applied to solve two case studies, one for optimizing the braces of 5-story frame, and the other for optimizing base isolator properties. The studies have proved that rapid implementation of optimization applications have been achieved by efficiently integrating two software conpoenents, and also exemplified the benefit of the integrated optimization for enabling practicing engineers to the improved solutions.

6. References

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