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Distributed NSGA-II for seismic retrofitting optimization with multi-core PC cluster

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1. Abstract
The distributed Genetic Algorithm (GA) for PC cluster with multi-core-CPUs is proposed as a time reducing method for determining the schemes of retrofitting existing buildings with Buckling restrained Brace (BRB). Non-dominated Sorting Genetic Algorithm-II (NSGA-II), one of the derivative evolutionary algorithm in heuristic method, was applied since the optimization problem have a multi-objective function. Two problem case was selected for validating performance of the distributed GA. The first case is seismic retrofitting of a two-dimensional steel frame structure with nonlinear static analysis, and the other one is seismic retrofitting of a three-dimensional reinforced concrete frame structure with nonlinear dynamic analysis. The objectives in both problems are minimization of cost for retrofitting and damage of retrofitted frame structure. To reduce the time for searching optimal solutions, the cluster computer consists of off-the-shelf Personal Computer (PC) with central processing unit (CPU) of quad-core processor was used. The PCs of the cluster were connected to local area network (LAN) through network switch have gigabits bandwidth. As a result, this study confirmed the possibility of using the cluster computer composed with multi-core-CPUs as High Performance Computing (HPC) for seismic retrofitting optimization.

2. Keywords: seismic retrofitting, buckling restrained braces (BRBs), design optimization, genetic algorithms (GA), personal computer cluster, multi-core-CPUs

3. Introduction
Buckling restrained braces (BRB), a kind of Hysteretic dampers (HD), is one of effective method for preventing the damage of main frame structure [1]. There are many research and application cases for using BRB for improving seismic capacity of the target building [2-6]. Conventional optimization algoritoms are not suitable for BRB retrofitting design optimization since the relation between changing of design variables and structural performance of the retrofitted building is discontinuous and nondifferentiable [7].
Although Genetic Algorithm (GA) can overcome the limits of conventional optimization algorithms, development of BRB retrofitting design optimization using GA have to manage the possible excessive computation time of repeated nonlinear structural analysis in iteration process of GA. For this reason, many researchers has try to apply personal computer (PC) cluster to structural optimization [8-15].
In this study, to improve the efficiency of existing retrofitting methods using BRB, the distributed GA-based optimal seismic retrofit design using BRBs for conjugating cluster of commercial PCs with multi-core CPU is suggested. The PC with i7-2600 quad-core processor [16] are connected to local area network (LAN) through switching network [17] have communication speed of Gbits per second.
The distributed GA is considering the communication configuration of PC cluster with multi-core-CPUs. Performance of The distributed GA was evaluated by applying to 2-dimensional retrofitting design optimization with nonlinear static structural anlaysis and 3-dimensional retrofitting design optimization with nonlinear dynamic structural anlaysis.

4. Formulation of retrofit design optimization problem

4.1 Design variables
In this study, circular hollow sections [18, 19] and rectangular section contained cross shaped steel core [18] are considered as BRB section. Material of the BRB are same as of Sarno and Elanshai's case. The section configuration of BRB installed at spans in target building is determined by width, depth, and thickness of steel core.

4.2 Objective functions

4.2.1 Objective function for 2D frames with nonlinear static analysis

Section area of steel core in BRB is dominant factor of total retrofitting cost while the area determine the capacity of BRB. Thus, first objective function f_i, which is minimizing total volume of steel core in the installed BRBs, is calculated in Equation 1 as presented below.

$$\text{Minimize } Objective\ f_1(\mathbf{x}) = \sum_{i=1}^{B} 2A_i l_i \qquad \text{Equation 1}$$

A_i and l_i are cross-sectional area and length of BRB installed at ith span. B is available spans to installed BRB. The volume is doubled because the BRB is installed as X shape at a span. Second objective function f_{2D-2} suggested Wen and Kang [20] is minimizing expecting lifetime seismic damage cost, and calculated in Equation 2 as below.

$$\text{Minimize } Objective\ f_{2D-2}(\mathbf{x}) = \frac{\upsilon}{\lambda}\left(1-e^{-\lambda t}\right)\sum_{i=1}^{k} C_i P_i \qquad \text{Equation 2}$$

υ is annual occurance probability. λ is lognormal distribution parameters in the seismic hazard distribution, t is expected lifetime of retrofitted building. k is the number of limit states as seismic damage. C_i and P_i are life-cycle cost and probability of a single hazard of ith damage state. P_i is calculated based on the interstory drift ratio Δ, as defined in Equations 3 and 4.

$$P_i = P(\Delta > \Delta_i) - P(\Delta > \Delta_{i+1}) \qquad \text{Equation 3}$$

$$P(\Delta > \Delta_i) = -\frac{1}{\upsilon \times t}\left\{\ln\left[1 - P_t(\Delta > \Delta_i)\right]\right\} \qquad \text{Equation 4}$$

Δ_i is interstory drift ratio, $P_t(\Delta > \Delta_i)$ is occurance probability of ith damage state through a period (0, t). In this study, seismic level have occurance probability of 50%, 10%, 2% during 50 years is considered for $P_t(\Delta > \Delta_i)$ [21].

4.2.2 Objective function for 3D frames with nonlinear dynamic analysis

In 3D frame optimization case, objective function for minimizing total volume of BRB is same as the Equation 1. On the other hand, to avoid excessive computation time, second objective function f_{3D-2} is the form of minimizing dissipated seismic energy at the main frame structure retrofitted by BRB [7, 22] , as defined in Equation 5.

$$\text{Minimize} \quad f_{3D-2}(\mathbf{X}) = \sum_{i=1}^{M}\int\left(V_i d_i + M_i\theta_i\right)dt$$
$$= \sum_{i=1}^{M}\sum_{t=1}^{N}\left[\frac{\left(V_i(t)+V_i(t+1)\right)}{2}\times\left(d_i(t+1)-d_i(t)\right)+\frac{\left(M_i(t+1)+M_i(t)\right)}{2}\times\left(\theta_i(t+1)+\theta_i(t)\right)\right]$$

Equation 5

V_i(t) and M_i(t) are shear force and moment of *j*th element at time step *t*. d_i(t)and θ_i(t) are deformation and rotation of *j*th element at time step *t*. *M* is the number of elemnt of the main frame, *N* is the number of points of inputed ground motion data.

4.3. Constrained conditions

To secure structural performance capacity of the retrofitted building, maximum interstory drift is regulated to be limited in allowable interstory drift ratio [21, 23, 24]. The condition about inter story-drift ratio is represented in Equation 7.

$$c = \Delta_{\max} / \Delta_a \le 1.0 \qquad \text{Equation 6}$$

$\Delta_{\max}$ is maximum interstory drift ratio in analysis, Δ_a is allowable interstory drift ratio. The allowable interstory drift ratio 2% is meaning structural performance level of life safety of braced steel frames and concrete frame in Table C1-3 FEMA-356 [25], and is middle value of heavy damage state range [26].

4.4. Distributed GA on multi-core PC cluster

The CPU of PC in the PC cluster is Intel Core i7 2600K which have 4 core processor of 3.4GHz clock rate [16]. The PC cluster consists of 16 of PC, which is meaning 16 of quad-core CPUs, 64 of core processor. The scheduler for parallelizaion of retrofitting design optimization algorithm is function of toolbox of MATLAB Distributed Computing Server (MDCS) [27]. The core processor as a master node, is also switched to a slave node, communicate with other core processor which is slave node through a network switch. It means that core processors in a PC have to share a LAN card of the PC, because the LAN card is only communication route of the PC. As a result, more frequent communication between master node and slave nodes casue more serious bottle-neck effect in the algorithm. In this study, considering the configuration of the PC cluster and GA which is containg nonlinear struatural analysis, the distributed GA is parallelized as candidate solutions level to minimize the number of communication times.

5. Performance of Distributed NSGA-II

Performance of the distributed NSGA-II was evaluated by the standard of global convergnace, computation time efficiency, and quality of optimal solutions while enlarging the number of core processors in the PC cluster as 1, 2, 4, 8, 16, 32, 64 (1/4, 1/2, 1, 2, 4, 8, 16 of quad-core CPUs). The optimization was repeated at each cases of the number of core processors because GA has probability.

Pareto-front lines from the repeated optimization trials were assessment to evaluate global convergence test. Computation time efficiency was mesearued by the speedup of elapsed computation time of generation part in GA. Ideal speedup Sideal was calculated by Amdahl's Law [28]. Improvement in structural quality was assessed by comparing the objective function values of candidate solutions to the values of not optimized case.

5.1. 2-dimensional steel frame structure case with nonlinear static analysis

The BRBs retrofitting design for existing steel moment resisting frames suggested by Sarno and Elnashai was selected as target building of 2-dimensional frame structure case [19].

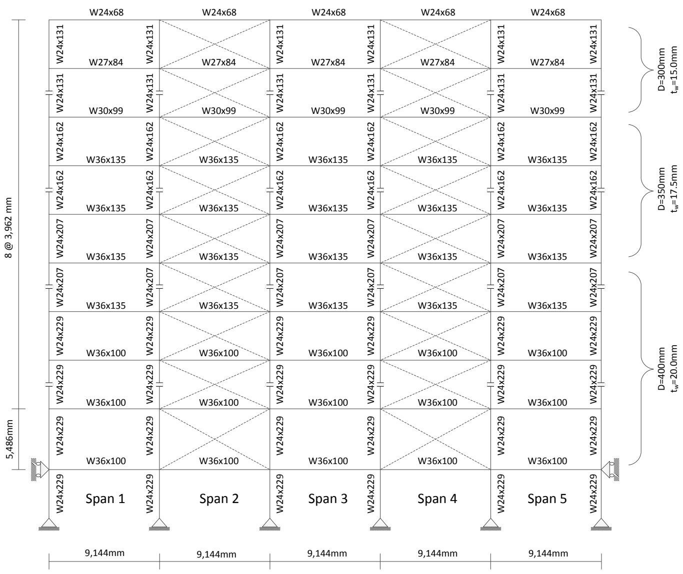

Figure 1: Scheme of 2D braced frame of Sarno and Elnashai

In this study, for considering most severe optimization case while securing the symmetry of the retrofitted building, the section area of BRB can be varied independently of the location of span, or story. Pushover analysis performed at seismic level of occurance propability 2% during 50 year. The analysis followed analysis procedure of FEMA 356.

Global convergence was confirmed by comparing all of Pareto-front solutions from repeated optimization trials to objective function value of Sarno and Elnashai's retrofitting case. At the same time, improvement of seismic capacity of the candidate solutions also evaluated by the Pareto-front solutions.

When using 64 of core processor (16 of quad-core CPUs), the distributed NSGA-II is 27.55 times faster than serial version. The efficiency of actual speedup related to ideal speedup are better than 83% except the case of using 32 of core processors (8 of quad-core CPUs), the efficiency of 79.07%. Actual speedup was decreased while used computation resources was increased. However, the tendency of the ratio of actual speedup to ideal speedup is not according size of computation recources.

5.2. 3-dimensional irregular reinforced concrete frame structure with nonlinear dynamic analysis case
BRB retrofitting optimization of SPEAR building was performed. The SPEAR building is 3-story reinforced concrete frame building has irregular plane, presented in figure as bellow.

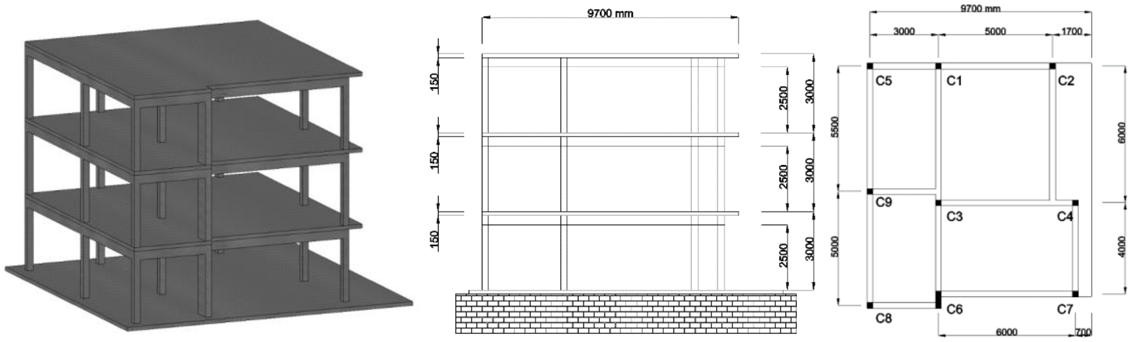

Figure 2: Configuration of SPEAR building before being optimized

The SPEAR building represents older construction in Greece and elsewhere in the Mediterranean region without engineered earthquake resistance since the SPEAR building was designed considering only gravity load only [29, 30].
In this study, the post-test model modified by Strantan and Fajfar was employed as analysis modeling of SPEAR building in BRB retrofitting design optimization. More specific information about the SPEAR building can be found in research of Fajfar [30, 31]. Nonlinear dynamic analysis is perfomed by using seismic input signal used in the research of Dolšek and Fajfar [32], presented in Figure 11.

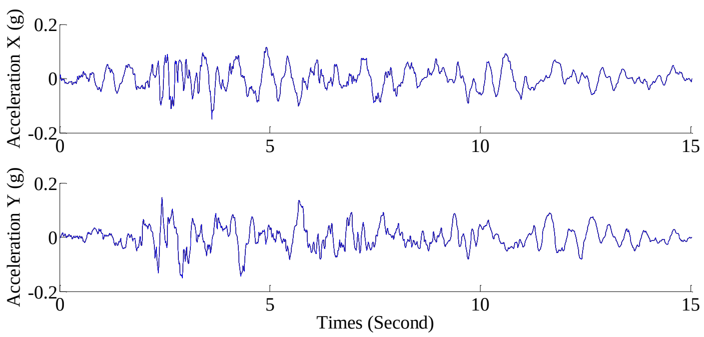

Figure 3: The time-history graph of bi-directional ground motion data normalized to PGA=0.15g

Global convergence was confirmed by comparing all of Pareto-front solutions from repeated optimization trials. Improvement of seismic capacity of the candidate solutions also evaluated by the Pareto-front solutions. Actual speedup was decreased while the size of computation resources was increased. However, the tendency of the ratio of actual speedup to ideal speedup is not according size of computation recources.
Elapsed time of parallelized part of 3-d irregular reinforced concrete frame structure case is increased from 98.52% to 99.85% since structural analysis of the case took 6 times as longer as computation time of 2-D case. The enlarged the ratio of parallelized part results improved parallelization efficiency. When using 64 of core processor (16 of quad-core CPUs), the distributed NSGA-II is 48.36 times faster than serial version. The efficiency of actual speedup related to ideal speedup are better than 80%. The tendency of the ratio of actual speedup to ideal speedup is not according size of computation recources as the tendency of 2-D case.

6. Conclusion

In this study, the distributed NSGA-II for multi-core PC cluster to overcome excessive copmputation time for BRB retrofitting design optimization was suggested and assessed the performance by applying to optimization problems. The distributed NSGA-II employed master-slave parallel model and performed on the PC cluster with 16 of quad-core CPUs. Performance of the algorithm assessed by the standard of global convergence, computation time efficiency, and quality of optimal solutions while applying the optimization problems.
Global convergence and improved quality of optimal solutions are confirmed by Pareto-front solutions from

repeated optimization trials of retrofitting problems. The fluctuation of actual speedup ratio have no certain relation with the number of core processors, but appeared similar tendancy at the both of optimization cases.
The ratio of actual speedup to ideal speedup of all optimization trials have minimum efficiency of 79.07%. Maximum actual speedups are 27.55 in 2-D and 48.36 in 3-D optimization case.
The decrease of the ration of actual speedup was diminished in 3-D optimization case than 2-D optimization case. Moreover, thare was phenomenon that the ratio of actual speedup to the ideal speedup is increased while using more core processors. In conclusion, the results of optimization trials show that stable and effective performance of the distributed NSGA-II with multi-core PC cluster

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