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Seismic performance-based design optimization considering direct economic loss and direct social loss

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ABSTRACT

Seismic performance-based design of a steel structure is performed using a multi-objective optimization that considers both direct economic and social losses. Specified performance objectives are considered as constraints and their variance over the obtained Pareto front is investigated. Optimization objectives are selected as the lifetime cost calculated from the initial construction cost and expected annual loss associated with seismic direct economic losses, and direct social loss parameter defined as expected annual social loss. Inelastic time history analysis is used to evaluate structural response under different levels of earthquake hazard to obtain engineering demand parameters. To illustrate the seismic performance-based design procedure, calculations are presented and compared for a sample steel structure located in Los Angeles, CA and Memphis, TN.

1. Introduction

The objective of seismic loss evaluation is to estimate and address the risks associated with having structures located in regions with high seismicity. Earthquake hazard impacts communities in various ways; from economic to social. Considering the impacts of economic and social losses should be an essential component of the structural design and decision making process. This study applies performance-based design (PBD) for structures and implements multi-objective optimization to minimize the potential losses associated with probable earthquake events. Seismic performance-based design (SPBD) is a process of designing new structures or upgrade existing structures to meet specified performance objectives for probable future earthquakes. Performance objectives are defined to quantify the building's behavior in seismic events in terms that would be meaningful and useful to all decision-makers [1]. PBD addresses performances at the system level in terms of risk of collapse, fatalities, repair costs and loss of function [2]. Seismic risk assessment combines hazard analysis with the relationship between intensity measures and seismic loss. Expected annual loss (EAL) is used as the seismic risk measure and is calculated in four major steps: probabilistic seismic hazard analysis, probabilistic seismic demand analysis, probabilistic capacity analysis, and probabilistic loss analysis [3–7]. The results of these four procedures are aggregated using the total probability theorem based on the framework presented by PEER (Pacific Earthquake Engineering Research Center) [6]. The evaluation procedure is a time-based assessment that considers different possible intensities of ground motion that might be experienced by building over a specific period of time [1]. In the PEER framework, losses due to structural performance are quantified by casualties, economic losses and, downtime (temporary loss of functionality) [8,9]. Economic losses as a measure of building performance have been considered in several studies [8,10–12]. In this study, to reflect different aspects of the seismic loss, two types of loss are considered in the calculations: direct economic loss and direct social loss. Direct economic loss expresses the probabilistic economic loss in probable future earthquakes as a percentage of the building replacement cost (%BRC). Direct social loss estimates the probabilistic casualty loss associated with an earthquake event. A multi-objective optimization is implemented to minimize the combination of the present value of the total economic cost (PC_t^T), considering initial cost and seismic economic loss for a lifetime period of structure, and expected annual social loss (EASL). The optimization is applied to the design of an example steel structure that resides in two different geographical regions: Memphis, TN located in Central United States and Los Angeles, CA, located in Western United States.

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Nomenclature

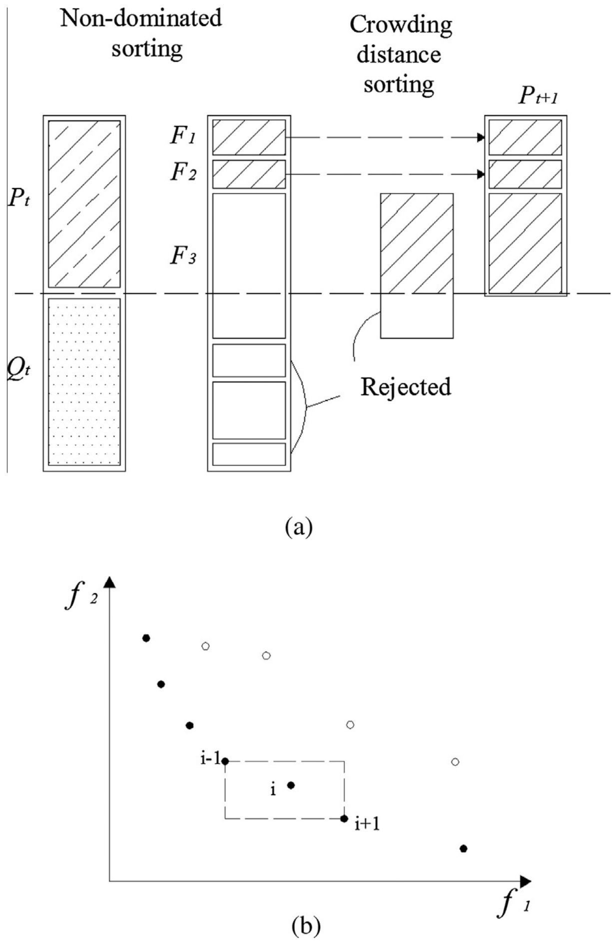
EAL	expected annual loss
EASL	expected annual social loss
TC	penalized value of the PC_t^T
PC_t^T	present value of the total economic cost
SL	penalized value of the EASL
φ	penalty function
CL_{CP}	confidence levels for collapse prevention
CL_{IO}	confidence levels for immediate occupancy
c_i	ith constraint
C_i	scaled ith constraint
DV	decision variable
DM	damage measure
EDP	engineering demand parameter
IM	intensity measure
L_c	direct economic loss for each component
L	direct economic loss
$RC_{DMi,c}$	repair cost for each component c
λ	annual rate of exceedance for each intensity measure
$\Delta\lambda_i$	change in annual rate of exceedance associated with dividing the hazard curve into m different segments
$SL_{outdoor}$	social loss associated with outdoor injuries
m	number of hazard levels considered
SL_{indoor}	social loss associated with indoor injuries
CSL_j	casualty severity level j
α	comprehensive cost for CSL_1($/person)
N_o	number of occupants in building
t	lifetime period
C^I	initial cost
PL_t^S	present value of the seismic direct economic loss
EN_{OI}	expected number of occupants injured or killed in an event
W	weight of the frame
ρ	cost per unit weight of the frame
i_r	discount rate
BRC	building replacement cost
λ_{CL}	confidence parameter
γ	demand variability factor
γ_a	analysis uncertainty factor
D	calculated demand on a structure
C	median estimate of the capacity of the structure
ϕ	uncertainty in the prediction of structural capacity
K_x	standard gaussian variant
β_{UT}	uncertainty measure
CL	confidence level

2. Optimization problem definition

A multi-objective genetic algorithm using an elitist non-dominated sorting strategy [13] is implemented to perform the optimization. In order to preserve the diversity of the solutions in the Pareto front, a crowding distance methodology is used. The steps of the implemented optimization method are:

- *Step 1:* Randomly generate a population P_n (size N).
- *Step 2:* Compute a fitness value for each parent individual in the population based on a non-dominated sorting. Fitness is assigned to individuals based on the number of solutions they dominate. An individual dominates another solution when it excels that solution in both objectives.
- *Step 3:* Generate a new child population Q_n (size N) based on general GA methodology (roulette wheel selection, uniform crossover, and mutation).
- *Step 4:* Develop a new population P_{n+1} from the parent and child populations (size $2N$) by grouping individuals into subsets of different fronts F_i based on the non-dominated sorting procedure. The next generation (size N) is populated with members for the first front F_1 (the most dominate front). If the new generation is not fully populated from the F_1 front pool, members are taken from the second front F_2, and so on, until the new generation P_{n+1} is fully populated. If there are fewer unfilled positions in the new generation than there are members in a front group, a crowding distance sorting strategy is applied where individuals with larger crowding distances (the distance between the individuals immediately before and after the individual j located on the Pareto front, as shown in Fig. 1b) are chosen to fill out the parent population.
- *Step 5:* If the maximum number of generations has not been met, repeat steps 2–4.

Fig. 1 is the graphical explanation of non-dominated sorting genetic algorithm (NSGA-II) implemented.



(a)

(b)

Fig. 1. Multi-objective optimization algorithm (a) NSGA-II procedure, and (b) crowding distance calculation [13].

Optimization objectives are defined as the lifetime cost of the structure or the present value of the total economic cost PC_t^T and direct social loss $EASL$. Therefore, the optimization problem would be