Probabilistic Scenario Approach to Structural Design

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Summary

Sustainability of infrastructure depends on the ability of designers to foresee future interactions between the building and its environment. Whereas representing these interactions as dead and live loads leads to satisfactory designs, additional consideration of specific events in the probabilistic space and application of advanced simulation techniques exhibits the potential to facilitate better and more sustainable design. To illustrate the event based analysis, scenario of localized failure due to malicious human activity is presented in this paper. Probability of building occupant survival is introduced as a measure to compare effectiveness of alternative designs. Since there are numerous possibilities of local failures, number of feasible scenarios were selected and analyzed using the Monte Carlo sampling. For localized failure, interaction between the building and its environment was characterized as a sudden removal of a key structural member. Such analysis is at the forefront of civil engineering modeling because it involves material nonlinearities, large deflections, finite strains, and certainly requires dynamic analysis. The modeling aspects (e.g. retrieving reliable structural information, probabilistic geometric inaccuracies, and material model) are presented. For each scenario, conditional probability of survival was calculated. Consecutively the theorem of total probability was used to evaluate the global probability of occupant survival for the considered array of events. Calculated scalar measure provides an opportunity to employ optimization algorithms to produce the safest structural design and save human lives in the case of abnormal loadings and/or unexpected hazards. In the proposed scenario based analysis, not only structural integrity after completion of construction is achieved, but also other specific objectives (e.g. high survivability in the case of abnormal loading). Presented methodology can be extrapolated to analyze fire resistance, flooding, truck impact, etc., in order to achieve desirable building characteristics and sustainable infrastructure.

Keywords: scenario based analysis, physics based simulation, steel frame building, numerical simulation, finite element method, LS DYNA, progressive collapse, column removal, abnormal loading, survivability, total probability, Monte Carlo simulation

1. Scenario Approach to Robustness Evaluation

The eveluation of the building robustness (resistance to progressive collapse) illustrates the proposed scenario based analysis. A Scenario based approach takes into account unusuall loadings. A realistic risk of a truck bomb was considered.

1.1 Probability of Occupant Survival given Localized Damage

Probability of an occupant survival was estimated using finite element dynamic simulations (LS-DYNA computer code). People occupying the collapsed floors usually suffer fatal injuries, whereas all other occupants of non-collapsed floors can be considered survivors. The ratio of the collapsed floor area to the total floor area of the building represented the probability of occupant's survival. Table 1 aggregates all the considered scenarios with their respective occupant's survival

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probabilities, P(S) as obtained from the LS-DYNA results. Twelve simulated scenarios were considered as a sample of the localized damage scenarios inflicted by the truck bomb.

Table 1: Probability of occupant's survival (inferred from the relative area of collapsed floors)

Detonation Zone I		Detonation Zone II		Detonation Zone III	
Removed Columns	P(S |D)	Removed Columns	P(S |D)	Removed Columns	P(S |D)
A1, A2, B1	0.87	A1, A2	1	A1	1
C1, D1, D2, E1	0	A1, B1	1	A2, A3	1
A2, A3, B3, A4	0	C1, D1, E1	1	A3, A4	1
		A2, A3, A4	1	C1, D1	1
				D1, E1	1

1.2 Probability of Localized Damage

The likelihood of an explosion in a particular zone depends on the building accessibility, parking and access road locations, natural barriers, etc. The position of a truck explosion can be described as a two dimensional probability density function (PDF). Such PDF describes a conditional probability of an explosion in a given location (depending on accessibility and other factors), should a terrorist attack occur. The probability of the truck explosion in a particular location was calculated using the areas of the pre-defined detonation zones.

1.3 Probability of Occupant Survival. Application of the Total Probability Theorem

The theorem of the total probability was employed to combine the conditional probabilities from an array of considered scenarios, into the one, final probability of the occupant's survival, should a truck explosion occur. Let T be the truck explosion, S the occupant's survival, and D the localized damage caused by the truck explosion. The probability of the occupant's survival is:

$$P(S \mid T) = \sum_{i=1}^{4} P(S \mid D_i) \cdot P(D_i \mid T) \tag{1}$$

$$P(S \mid T) = 0.87 \cdot 0.18 + 0 \cdot 0.25 + 1 \cdot 0.22 + 1 \cdot 0.35 = 0.73 \tag{2}$$

2. Conclusions

A considerable gap between structural engineers and building owners exist in terms of understanding structural safety. Whereas structural engineers focus on stress states, building owners are concerned with financial dimensions and occupants' safety. A broader approach to structural design and building evaluation was introduced in this paper to provide holistic, probability based on information on building safety. The main objective of this paper was to present a scenario based approach to structural analysis. Probability of occupant's survival was introduced as the scalar objective function as opposed to the traditional allowable stress analysis. Practical procedure for the survival probability calculations by means of physics based simulations and theorem of total probability was explained.

Firstly, for the given column removal scenarios, the area of collapsed floors were extracted from the physics based simulations. People occupying the collapsed floors usually suffer fatal injuries, whereas all other occupants of non-collapsed floors can be considered survivors. The ratio of the collapsed floor area to the total floor area of the building represented the probability of occupant's survival. Consecutively, the likelihoods of the twelve sampled localized failures were calculated using the assumed TNT equivalent mass and stand-off distance to the building perimeter.

Thus, the goodness of design was quantified with the survival probability of a building occupant. Such a single scalar measure is critical in order to combine the outcomes of numerous feasible loading scenarios into the useful information for the building owners.