RISK-BASED DECISION ANALYSIS FOR BUILDING SERVICEABILITY

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Abstract

Serviceability is an important design criterion for tall buildings. The cost associated with occupant discomfort leading to building shut down are significant if the prescribed acceleration levels are exceeded. One of the options for reducing response due to wind and seismic loading is to introduce inertial devices like tuned mass dampers and tuned liquid dampers. A simplified example is chosen to illustrate the increase in reliability as a result of adding passive and semi-active liquid dampers. The semi-active liquid damper has the provision of adjusting its headloss coefficient in order to maintain the optimal damping at all levels of excitation. FORM/SORM techniques are used to determine the probability of failure due to acceleration levels exceeding the prescribed comfort level. These are later integrated into a decision analysis framework. These decisions are important in design, construction, operation and maintenance of the damper systems for the building. The framework presented here would facilitate convenient implementation of a strategy that ensures an adequate level of reliability at the lowest possible life-cycle cost.

Introduction

Serviceability is an important factor in the design of tall buildings under wind loading. There are primarily two types of adverse serviceability conditions caused by strong winds. The first is that excessive wind may cause large deflections in the structure causing architectural damage to non-structural members like cladding and elevator operation. The other is the oscillatory motion which may cause occupant discomfort or even panic. It is generally accepted that acceleration and the rate of change of acceleration (commonly known as *jerk*) are the main causes of human discomfort. Usually, the risk of unserviceability (i.e. excessive deflections or accelerations) is calculated assuming that failure occurs when the deflection or acceleration exceeds a certain specified value.

The example considered in this paper is merely for illustration purposes. However, the framework presented is very general and could be applied to any system. The building considered is a 60 story, 183 m tall building with a square base of 31 *X* 31 m. Designers are considering the option of adding a liquid damper as a viable choice for increasing the serviceability of this building under winds. Essentially, liquid dampers are inertial devices for reducing motions of the primary structure, similar to tuned mass dampers (Xu *et al*. 1992). Like TMDs, the effectiveness of these dampers depends on tuning ratio and damping ratio of the device (Yalla *et al*. 1998). Two types of tuned liquid column dampers (TLCDs) are being considered for this application. The first is a passive system in which the frequency of liquid oscillations is tuned to the first mode frequency of the building while the damping is not always optimal since it varies with the level of building response. The second is a semi-active system, in which the optimal level of damping is maintained at all levels of response. This is important because the damping introduced by the TLCD through an orifice is amplitude dependent. Therefore an adjustable orifice is needed to maintain the optimal level of damping. However, an increase of 15-25% in effectiveness over the passive system overrides the extra costs associated with this system. Figure 1(a) shows the structure equipped with the TLCD. The RMS acceleration of the uncontrolled building is plotted as a function of the mean wind velocity at 10m height (Fig. 1(b)).

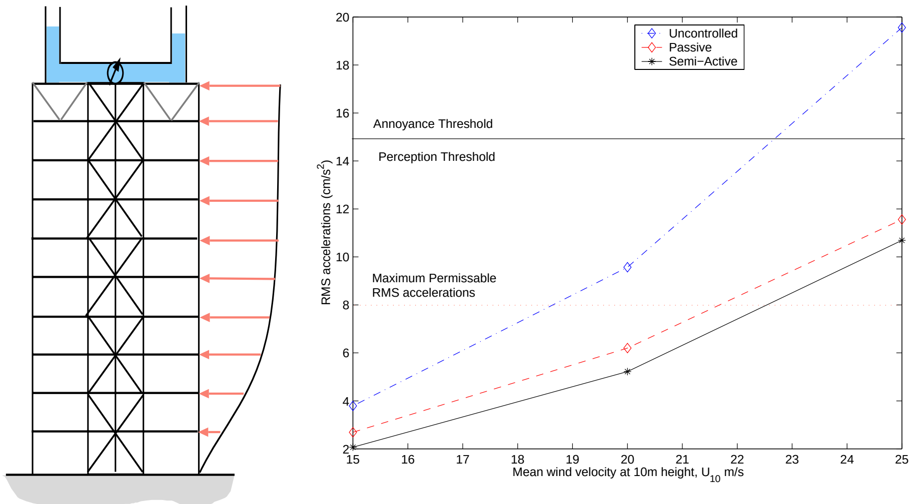

Figure 1. A schematic of the TLCD system on a structure (b) Variation of RMS accelerations of the top floor with increasing wind velocity

Decision analysis framework

The decision making framework is commonly composed of the following components:

Objectives of Decision analysis: Decision analysis problems require an objective function(s) to be clearly defined. In our present example this could be minimizing the total expected cost or utility value.

Decision variables: These could be the various decision alternatives available to the owner of the building. In our example, perhaps, these are the following alternatives available to designers:

1. Do not take any action to improve building serviceability.
2. Invest in traditional bracing/outrigger systems to increase the lateral stiffness. The net increase in the effective stiffness of the resulting structure due to the addition of bracing is given by a factor *kf* defined as the ratio of the stiffness with bracing added to stiffness without additional bracing.
3. Install passive liquid dampers with the optimal tuning ratio and non-optimal damping. This is a sub-optimal configuration of the liquid dampers, the damping is primarily due to headloss due to friction in the tube and fixed orifice.
4. Install semi-active controllable passive liquid damper which maintains the optimal damping at all levels of response.

Decision outcomes: Decision alternatives may have the following outcomes:

1. Building serviceability would be severely compromised leading to building shutdown. An important function to be determined would be the associated costs for an unserviceable structure.
2. Bracing systems and outrigger systems are costly and are not so effective in reducing the acceleration which is the primary source of serviceability problem.
3. The passive liquid damper devices are effective in reducing displacements and accelerations, however their performance could be drastically improved by adjusting the damping.
4. Controllable passive devices are more effective than the passive ones, however, there are additional costs for controllable valves, computer control system, sensors and maintenance.

Associated Probabilities and Consequences: In the next sections, methods to estimate the probabilities of failure and the associated costs/utility values of each decison are examined. Finally these are integrated into a risk-analysis decision analysis tree. The risk of an event is defined as the following

$$\text{Risk of an event} = \text{Occurrence Probability X Occurrence Consequence} \tag{1}$$

Deterministic Analysis

Deterministic analyses were carried out for uncontrolled building under wind loads and with passive and semi-active systems. Computational details are omitted here for brevity. It is obvious that the dampers are effective in reducing the building acceleration and displacements in the response (Fig. 1(b) & Table 1). In case of added bracing, an increase in the stiffness is implied. Moreover, as seen from table 1, the added bracing is effective in reducing displacements but not so effective in reducing accelerations. In the case of a liquid damper, for the passive case, the damping is assumed to be arising due to the inherent damping in the liquid column and fixed orifice. The headloss coefficient for this case is assumed to be equal to 1, which is typical of such a system. In the case of semi-active system, the optimal damping ratio of 5.5% is maintained at all levels of excitation by means of a controllable orifice (Yalla and Kareem, 2000). The total mass ratio of the damper to the first modal mass is taken as 1% and the tuning ratio is 0.99 which corresponds to a total mass of 280 tons and 12 meters long liquid column.

	RMS displacement $U_{10} = 15 m/s$ *(cm)*	*RMS displacement* $U_{10} = 20 m/s$ *(cm)*	*RMS displacement* $U_{10} = 25 m/s$ *(cm)*	*RMS acceleration* $U_{10} = 15 m/s$ *(cm/sec^2)*	*RMS acceleration* $U_{10} = 20 m/s$ *(cm/sec^2)*	*RMS acceleration* $U_{10} = 25 m/s$ *(cm/sec^2)*
Uncontrolled	2.37	5.97	12.19	3.79	9.57	19.56
Added Bracing	1.54 (30.4 %)	3.87 (35.1 %)	7.92 (35 %)	2.95 (22.1 %)	7.44 (22.2 %)	15.23 (22.1 %)
Passive	1.73 (23.4 %)	3.93 (34.1 %)	7.17 (41.2 %)	2.69 (29 %)	6.20 (35.2 %)	11.56 (40.9 %)
Semi-Active	1.26 (40.6 %)	3.18 (46.7 %)	6.49 (46.7 %)	2.07 (45.4 %)	5.22 (45.4 %)	10.69 (45.3 %)

Table 1: Deterministic Analysis for Top floor of the Structure

Probability of Failure

The serviceability criteria is defined as a limit state function given as:

$$Z = g(X_1, X_2, \ldots, X_n) \tag{2}$$

and the probability of failure P_f for the component is defined as:

$$P_f = P(Z < 0) = P[g(X_1, X_2, \ldots, X_n) < 0] \tag{3}$$

Usually, FORM/SORM methods are used where the limit state is approximated at the design point on the failure surface. This procedure involves transformation of the variables in the limit state equation to reduced normal variates which yields a new limit state equation in the reduced space. The probability of failure is then determined from the *reliability index*, which is defined as the shortest distance from the origin to the a failure surface.

The limit state equation for *serviceability* is expressed as,

$$Z = \sigma_{ma} - \sigma_{\ddot{x}} \tag{4}$$

where σ_{ma} is the maximum allowable RMS accelerations commonly taken as 5mg-15mg as in the perception threshold range and 15mg-50mg in the annoyance level as shown in Fig. 1(b). In this study we are primarily concerned with the comfort criteria. Therefore, σ_{ma} equal to 8, 10 and 12 mg has been considered. The random variables used in the reliability analysis are listed in table 2. The extreme wind velocity for a well behaved wind climate can be adequately modeled by a Type 1 extreme value distribution. The other variables, their probability distributions and their coefficient of variations (COVs) are given in table 2. Probabilities of failure of the system with the three systems under different mean wind velocities and different σ_{ma} are shown in Table 3.

Type	*#.*	*Random Variable*	*Probability Distribution*	*Mean*	*COV*
Structural Parameters	1	Mass of each floor, *m*	Log Normal	1.0	0.1
	2	Stiffness of each floor, *k*	Log Normal	1.0	0.25
	3	1sr mode damping, ζ	Log Normal	1 %	0.5
Wind Load Parameters	4	Air density, ρ	Log Normal	1.25 kg/m^3	0.05
	5	Drag coefficient, C_d	Log Normal	1.2	0.17
	6	Power law exponent, α	Log Normal	0.3	0.1
	7	Mean Wind Velocity, *V*	Extreme Value Type 1	40, 50 m/s	0.1
Liquid Damper Parameters	8	Tuning ratio, γ	Log Normal	0.9870	0.1
	9	Coefficient of Headloss, ξ	Log Normal	1	0.1
	10	Optimal Damping, ζ_d	Log Normal	5.5 %	0.05
Bracing	11	Stiffness factor, *kf*	Log Normal	1.2	0.2

Table 2: Random Variables used in the Reliability analysis

Probability of Failure (%)	U_{10} = 18 m/s		U_{10} = 20 m/s	
	σ_{ma} =8 mg	σ_{ma} =10 mg	σ_{ma} =10 mg	σ_{ma} =12 mg
Uncontrolled	39.34 %	14.21 %	44.43 %	29.87 %
Braced System	33.43 %	11.12 %	40.23 %	24.71 %
Passive System	14.86 %	3.66 %	23.17 %	8.79 %
Semi-Active Case	4.69 %	0.71 %	10.28 %	2.69 %

Table 3: Probabilities of Failure under different mean wind conditions and allowable RMS acceleration limits

Cost Analysis

A generalized total expected cost function (for a period of T years) can be written as:

$$C_t = C_s + C_d + \int_0^T C_m(t)dt + \int_0^T C_f(t)dt \tag{5}$$

where C_s is the initial fixed cost of the structure, C_d is the initial fixed cost of the damper, C_m is the maintenance cost per unit year and C_f is the repair/business interruption cost per unit year. The estimation of these cost functions requires a detailed analysis of the system at hand. In particular, the one cost which is hard to quantify is C_f which is a function of various factors, e.g., local market value and real estate demand. For a simplified analysis, this can be written as:

$$C_f = TP_f C(E) \tag{6}$$

where $C(E)$ is the cost of repair/ business interruption/ decreased employee productivity when the event E occurs. In this analysis it has been assumed to be equal to 10. Table 4 tabulates some general costs and utilities of a typical tall building. Most of these figures are arrived at in an empirical way, however, the framework for more market value based cost analysis would remain the same.

Fixed Costs (Cost of structure (C_s) same for all options)	*Dollar values*	*Utility*
Amount of Steel, construction costs, loss of floor space	2.5%	5
Cost of liquid tanks, loss of floor space, maintenance	0.5%	1
Costs of liquid tanks, controllable valve, design and consulting fees, computer controlled system, maintenance	1%	2

Table 4: Costs and Normalized Utility Analysis

Risk-based Decision Analysis

Figure 2 shows a typical decision tree used to examine the given problem in a systematic format. The decision tree includes decision and chance nodes. The decision nodes are followed by possible actions which the decision maker takes. The chance nodes are followed by outcomes that are beyond the control of the decision maker. The total expected utility for each branch can be computed and the decision is selected such that the expected total utility is minimized.

Total Utility	*U_{10} = 18 m/s*		*U_{10} = 20 m/s*	
	σ_{ma} =8 mg	σ_{ma} =10 mg	σ_{ma} =10 mg	σ_{ma} =12 mg
Uncontrolled (C_A)	7.86	2.84	8.88	5.97
Braced System (C_B)	11.68	7.24	13.08	9.94
Passive System (C_C)	3.97	1.73	5.63	2.75
Semi-Active Case (C_D)	2.93	2.14	4.05	2.53

Table 5: Utility analysis based on the decision analysis

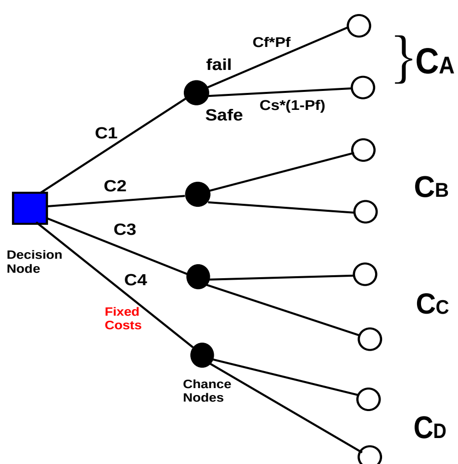

Figure 2: Decision Tree for Building Serviceability

As seen from table 5, when the probabilities of failure are low, there is not much sense in choosing semi-active dampers as passive dampers would deliver a similar performance in terms of cost. However, in critically unserviceable structures, the semi-active scheme delivers better cost benefits.

Conclusions

A general probablistic framework for decision analysis concerning the serviceability of a building has been presented. Both deterministic and reliability analyses show the attractiveness of the passive and semi-active liquid dampers in reducing acceleration response and in the associated probability of failure. The decision analysis framework presented here would facilitate building owners/designers to ensure adequate reliability of the building from serviceability viewpoint at a minimum cost.

Acknowledgements

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