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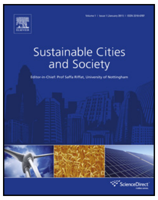

Review

Toward greater building earthquake resilience using concept of critical excitation: A review

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ABSTRACT

The words of 'unexpected issue' and 'earthquake resilience' are frequently used after the 2011 off the Pacific coast of Tohoku earthquake which occurred March 11, 2011. Although the unexpected issues are hard to include in the structural design stage of civil structures, those certainly decrease the earthquake resilience of those civil structures. Once these unexpected issues are taken into account in the structural design, those issues become expected issues. However these repetitions of cycles, i.e. experiences of unexpected issues during earthquakes and incorporation into design codes, never resolve the essential problems in structural earthquake engineering.

In this paper, a historical review is made on the development of critical excitation methods as worst-scenario analysis and some possibilities of application of this concept to upgrading of building earthquake resilience are discussed.

Contents

1. Introduction

The word of 'earthquake resilience' is frequently used especially after the 2011 off the Pacific coast of Tohoku earthquake which occurred March 11, 2011. Earthquake resilience is utilized in various fields including society, community and structural engineering

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etc. It implies the ability or capability to recover from certain damaged states or the toughness not to be damaged against various disturbances. As far as the earthquake structural engineering is concerned, when structural designers try to investigate the earthquake resilience, they have to evaluate the earthquake performances of building structures with various uncertainties under broader range of earthquake ground motions, preferably for critical excitation.

Since Drenick's pioneering work in 1970, the critical excitation methods have been tackled from various viewpoints. The critical input to a structure is a resonant wave to the structure. Most earthquake engineers believed that such phenomena never occur in a real world. However, some examples were actually observed during Mexico (1985), Northridge (1994), Kobe (1995), Tohoku (2011).

An efficient methodology is required to evaluate the robustness (degree of insensitiveness of response) of a building with uncertain structural properties under uncertain ground motions. It is well known (Fujita & Takewaki, 2011a, 2011b, 2011c, 2012a,b; Takewaki, Moustafa, & Fujita, 2012) that base-isolated buildings and structural controlled buildings have large structural uncertainties due to wide variability of base-isolation members and passive dampers for structural control caused by temperature and frequency dependencies, manufacturing errors and aging effect than earthquake resistant buildings. This procedure of taking large variability into account is well established in Japan in the actual structural design stage of high-rise and base-isolated buildings. Furthermore, after the devastating disaster of the 2011 off the Pacific coast of Tohoku earthquake in Japan, it is under discussion that base-isolated buildings are vulnerable against unexpected long-period ground motions. In fact, it is reported that some base-isolated buildings exhibited unfavorable behavior.

Under these circumstances, it is desired to evaluate the response variability caused by such structural variability and uncertain ground motions (Elishakoff & Ohsaki, 2010; Takewaki, Fujita, Yamamoto, & Takabatake, 2011; Takewaki, Murakami, Fujita, Yoshitomi, & Tsuji, 2011). The method based on the convex model may be one possibility (Ben-Haim & Elishakoff, 1990). This will be reviewed in the following section. Introduction of a bound on Fourier amplitude of input ground motions may be another approach (Takewaki & Fujita, 2009). Independently, Kanno and Takewaki (2005, 2006a, 2006b, 2006c) proposed an efficient and reliable method for evaluating the robustness of structures under uncertainties based on the concept of the robustness function (Ben-Haim, 2001; Takewaki & Ben-Haim, 2005). This will also be reviewed in the following section. However it does not appear that an efficient and reliable method for evaluating the robustness of structures has been proposed.

An interval analysis is believed to be one of the most efficient and reliable methods to respond to this requirement. The interval analysis is aimed at finding the worst combination of uncertain parameters which attains the maximum or minimum objective function. While a basic assumption of "*inclusion monotonic*" is introduced in usual interval analysis, a possibility should be taken into account of occurrence of the extreme value of the objective function in an inner feasible domain of the interval parameters for more accurate and reliable evaluation of the objective function. This is very difficult because the number of combinations from finite to infinite. It is shown that the critical combination of the structural parameters can be derived explicitly by maximizing the objective function by the use of the second-order Taylor series expansion. This method is called the URP (Updated Reference-Point) method (Fujita & Takewaki, 2011a, 2011b, 2011c). When nonlinear elastic–plastic responses are dealt with, it is useful to introduce an approximate objective function by the use of the method combining the URP method (Fujita & Takewaki, 2011a, 2011b, 2011c) with a kind of response surface method (Fujita & Takewaki, 2012a).

2. Robustness, redundancy and resilience

In the field of structural engineering, robustness, redundancy and resilience play an important role in order to guarantee the safety of infrastructures against severe disturbances, e.g. earthquakes, strong winds, impacts. Progressive collapse has to be avoided absolutely because progressive collapse often leads to a catastrophic damage. Progressive collapse is sometimes defined as follows:

> *Spread of local damage, from an initiating event, from element to element resulting, eventually, in the collapse of an entire structure or a disproportionately large part of it; also known as disproportionate collapse* (ASCE, 2005; Ellingwood et al., 2006).

A multiplex safety, often called fail-safe, may be of significance from the viewpoint of response to unexpected issues. The concepts of robustness, redundancy and resilience are closely interrelated. In general, robustness means insensitiveness of a system to parameter variation and implies toughness to disturbances (Ben-Haim, 2001; Kanno & Takewaki, 2005, 2006a, 2006b, 2006c, 2007; Takewaki, 2008a; Takewaki & Ben-Haim, 2005). On the other hand, redundancy indicates the degree of safety, frequently expressed by a safety factor (Doorn & Hansson, 2011), of a system against disturbances or the connectivity of components. In the latter meaning, a parallel system is regarded as a preferable system able to avoid sudden overall system failure (the fail-safe system is a representative one). Resilience can be regarded as an ability of a system to recover from a damaged state or resist external disturbances and seems to be a more generic concept including robustness and redundancy (Takewaki, Fujita, et al., 2011; Takewaki, Moustafa, et al., 2012). Recently the concept of resilience is getting much interest in broad fields of society (Committee on National Earthquake Resilience, 2011; Ellingwood et al., 2006; Poland, 2012; Takewaki, Fujita, et al., 2011). In the report of Committee on National Earthquake Resilience (2011), there are some explanations. The followings are examples.

> "The capability of an asset, system, or network to maintain its function or recover from a terrorist attack or any other incident" (DHS, 2006).
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> "The capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure. This is determined by the degree to which the social system is capable of organizing itself to increase this capacity for learning from past disasters for better future protection and to improve risk reduction measures" (UN ISDR, 2006).
>
> "The ability of social units (e.g., organizations, communities) to mitigate risk and contain the effects of disasters, and carry out recovery activities in ways that minimize social disruption while also minimizing the effects of future disasters. Disaster Resilience may be characterized by reduced likelihood of damage to and failure of critical infrastructure, systems, and components; reduced injuries, lives lost, damage, and negative economic and social impacts; and reduced time required to restore a specific system or set of systems to normal or pre-disaster levels of functionality" (MCEER, 2008).

The term of resilience is often used loosely, vaguely and inconsistently (Committee on National Earthquake Resilience, 2011). After some useful discussions, the following definition is summarized in the report of Committee on National Earthquake Resilience (2011).