Chapter 11

Smart Structures

Field of Expertise: Structural and Earthquake Engineering

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Summary

A smart structure is a structural system equipped with devices to measure and control its response when subjected to external excitations, such as earthquakes and strong winds. This structural system is a promising measure to mitigate seismic damage from severe earthquakes, such as the Nankai Megathrust Earthquake expected to occur within the next 30 years. This chapter discusses the realization of smart structures and state-of-the-art structural health monitoring techniques.

Keywords: Smart structure, long-period ground motion, high-rise building, structural health monitoring, damage detection

Introduction

Thousands of high-rise and base-isolated buildings, classified as long-period structures, have been built in Japan. During the 2011 Great East Japan Earthquake, these structures were subjected to long-duration shaking induced by long-period ground motions. Since then, the issue of long-period structures subjected to long-period, long-duration ground motions has been taken seriously by the Japanese structural engineering community. To address this issue, we briefly describe our activities.

1: Problems Revealed by the Great East Japan Earthquake

What happened?

During the Great East Japan Earthquake (magnitude 9.0) on March 11, 2011, many seismometers located in the Tohoku region recorded very high acceleration values exceeding the acceleration due to gravity (= 9.8 m/s^2). This high acceleration induced the falling of ceilings in many gymnasiums and other large-span structures that were expected to serve as evacuation stations in the event of a disaster. Consequently, many of these structures were not functional for the anticipated purpose. However, the recorded data did not significantly contain the “killer pulse” component within the range of 0.5 to 1 Hz, which is known to affect low-rise structures critically. Because of their characteristics, low-rise buildings (for example, detached houses) were not as significantly damaged during this earthquake as during the 1995 Kobe Earthquake, in which the killer pulse component predominated1).

In contrast, many high-rise buildings in Tokyo, located more than 300 km away from the epicenter, were significantly shaken by long-period ground motions for up to 10 min, resulting in malfunctions and failures of non-structural components. Furthermore, a 55-story building constructed on reclaimed land near Osaka Bay, approximately 770 km from the epicenter, underwent prolonged shaking for approximately 10 min; its top floor shook up to 2.7m horizontally. A subsequent survey revealed that the number of damages amounted to approximately 360, including the falling of ceiling components and cracks on the floors. The Great East Japan Earthquake indicated that attention should be paid to high-rise buildings subjected to near-fault earthquakes and far-field mega-earthquakes.

Many high-rise buildings in the vast area of eastern Japan were influenced by this strong earthquake. There was an increasing demand to assess the post-earthquake structural conditions because the safety of buildings needed to be guaranteed against subsequent aftershocks. However, visual inspection relying on human effort is not the best method in such a disastrous situation because it requires inspectors to work under high risks of aftershocks in potentially unsafe buildings. The importance of structural health monitoring (SHM) techniques that do not significantly rely on human effort has been widely recognized by the Japanese structural engineering community.

The Great East Japan Earthquake identified the importance of the following challenges.

1) Enhancement of the seismic performance of high-rise buildings
2) Postearthquake structural condition assessment based on measurement data

In this regard, we summarize our efforts on the above and highlight the future challenges in the following sections.

1. Smart structural systems to enhance seismic capability of high-rise buildings

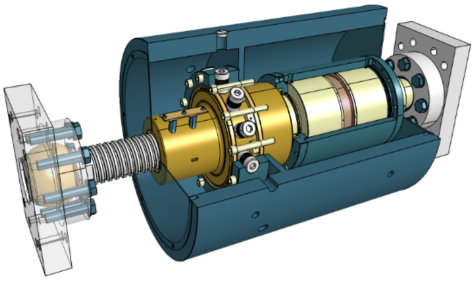
Fig. 1 Rotary inerter damper


Fig. 2 Variable orifice damper

The fundamental concept of a smart structure can be understood from the analogy of a person standing on a vehicle, such as a train or a bus. When the vehicle moves suddenly, the person steps on his or her feet or holds a strap to maintain stability for safety. This behavior is somewhat natural when we are on a board, and smart structures also have functionalities similar to earthquakes. In a smart structure (human), measured data in sensing devices (senses) are transferred to a computer (the brain), and a dynamic jack (muscles) moves for safety.

The unprecedently high economic growth of Japan from the late 1980s to the early 1990s facilitated the construction of smart structures. However, this prosperous period did not last long and declined, partly because of the end of the high-growth period and concerns about its performance. For example, a smart structure stops functioning if a power failure occurs during a disaster (for example, an earthquake or typhoon), or it might accelerate the structural damage, owing to the unexpected behavior or malfunction of dynamic actuation systems.

Although the same situation for this structural system prevailed even after 2000, the classical passive vibration control approach was recently revitalized and recognized as another form of smart structure. The dynamic vibration absorber and tuned mass damper (TMD) are examples. Currently, a high-rise building in Shinjuku, Tokyo, is equipped with TMDs (with a total weight of 1,800 tons) as a countermeasure against long-period motions[2]. When this building is shaken by seismic motions or strong winds, its pendulums suppress the vibration. As shown above, the passive approach does not require sensors or dynamic actuation systems driven by electricity, which are vital elements of the conventional smart structure. However, in this approach, the suspended weights passively sense their structural vibrations, and an energy-absorbing device attached to the mass controls the vibration without using electricity. Because of this feature, the passive approach is generally regarded as more cost-effective and reliable than the active approach, which relies on electricity. This cost-effective aspect promotes its application in practice, which will become mainstream in enhancing the seismic capability of high-rise buildings.

Our research group at Tohoku University and private companies jointly developed passive devices to construct passive smart structures. One of the devices was an inerter-based device (Fig. 1), and the other was a variable orifice damper (Fig. 2). The rotary inerter damper records an apparent mass several thousand times larger than the physical mass of the cylindrical flywheel via a ball-screw mechanism, which converts linear motion into rotational motion. This device is innovative in decreasing the weight of the device, although conventional TMDs typically require hundreds or thousands of weight larger than this innovative device. This device has already been used to retrofit three actual high-rise buildings. A variable orifice damper was developed to suppress excessive displacement in a base-isolated structure, particularly under long-period ground motion. This device increases the control force when the displacement of the structure exceeds the prescribed limit. The research and development of this device are actively in progress for applications in actual structures.

2. SHM techniques for post-earthquake assessment

Visual inspection is the most straightforward approach for detecting structural damage and its severity in a building. However, inspection accuracy depends on the experience and skill of the inspectors and the visibility of damage. Different SHM techniques have been developed based on the data acquired using measurement equipment placed on the structure to minimize reliance on visual inspection. The frequency-domain approach, one of the most widely used SHM techniques, is typically effective only for global structural condition assessment. However, this approach is unsuitable for local assessments, which require more detailed information, such as the location and severity of structural damage. For local assessments in SHM, a technique for directly evaluating the physical parameters of damaged structures is required.

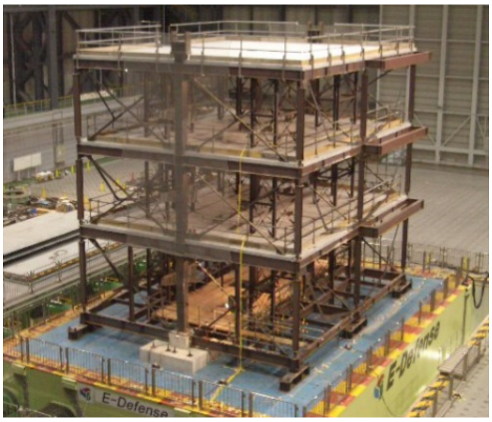
Fig. 3 E-Defense test with three-story structure.

To address this requirement, we developed a method called simple piecewise linearisation in time series (SPLiTS)[3], which identifies the physical parameters of a structure shaken by an earthquake. Its efficiency was verified through shake table tests on a full-scale three-story steel structure (width: depth: height = 18 m: 12 m: 13.5 m; total weight = 140 t), as shown in Fig. 3. The shake table tests were performed at E-Defense, the world’s largest 3D shake table testing facility. SPLiTS detected changes in the stiffness and damping of the structure in the time history and structural energy absorption, as shown in Fig. 4. It was also found that SPLiTS could provide information on the time of occurrence and severity of structural damage.

Current SPLiTS requires acquiring acceleration and displacement data using measurement devices on each floor. In terms of SPLiTS applications, acquiring displacement data is challenging, although obtaining acceleration data is significantly easier because of recent advancements in wireless sensing technology. For its application to structures in cities, the current SPLiTS should be investigated to achieve similar estimation accuracy using only acceleration data without relying on displacement data.

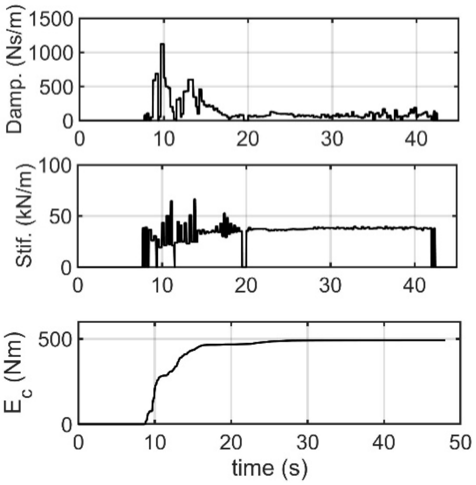

Fig. 4 Results of SPLiTS

Epilogue

From past severe earthquakes, Japan has learned that various factors associated with earthquakes lead to significant casualties and loss of property: the tsunami during the 2011 Great East Japan Earthquake, the collapse of structures during the 1995 Kobe Earthquake, and the fire of the 1923 Great Kanto Earthquake. Earthquakes are unpredictable in terms of their occurrence dates, locations, and degree of severity. Several factors that increase the risk of loss and casualty need to be considered during preparation to mitigate losses caused by such unpredictable disasters. From a long-term perspective, we are applying various advanced techniques, such as artificial intelligence, control theory, and wireless technology, to structural control and SHM to prompt preparation against future strong earthquakes.

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