



Practical implementation of anti-catastrophe concept in terms of structural control and restoration

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Abstract

Recent large earthquakes in Japan including the 2011 Great East Japan earthquake and the 2016 Kumamoto earthquake caused not only damage and collapse of structures due to strong ground motions, but also washout of structures due to the subsequent giant tsunami and huge landslide. In addition, long-term material deterioration might have a significant impact on seismic damage to structures. Although strong ground motion is still a dominant hazard to structures in many earthquake-prone countries, multiple hazards (i.e. independent and/or interacting hazards) causing structural failure have to be considered when estimating the seismic safety, reliability and risk. It is expected that the structural damage and the monetary loss due to the ground motion and tsunami caused by the anticipated Nankai Trough earthquake would be larger than those resulting from the 2011 Great East Japan earthquake. A need to include the anti-catastrophe concept into the structural design and assessment is discussed in the present paper based on the lessons from recent large earthquakes in Japan. In addition to the quantifications of risk and resilience associated with damage to structures and civil infrastructure systems under extreme events, research studies on implementation of anti-catastrophe concept in terms of structural control and restoration of structures must be developed more before the occurrence of the anticipated Nankai Trough earthquake. These research topics based on the author's previous studies are introduced herein.

Keywords: anti-catastrophe; bridges; multiple hazards; risk; resilience; earthquake resistant structure.

1. Introduction

Several destructive earthquakes in Japan inflicted various levels of damage on structures and infrastructure systems. When subjected to strong ground motions, they have the potential to exhibit brittle failure. The investigation of these negative consequences gave rise to serious discussions about seismic design philosophy, and to extensive research activity on the retrofit of as-built structures [1]. The 2011 Great East Japan earthquake and the 2016 Kumamoto earthquake demonstrated that many structures and civil infrastructure systems were damaged and collapsed not only due to the strong ground motions, but also due to the subsequent giant tsunami and huge landslides [2]. Largescale hazards can damage many structures in an existing transportation system simultaneously. The prompt restoration of critical transportation networks after an extreme event is always a goal of paramount importance, since it plays a crucial role in the evacuation of affected people and the transportation of emergency goods and materials [3, 4]. To quantify the promptness of the restoration, it has become customary to use the concept of resilience. Based on the lessons from the recent large earthquakes, a significant amount of research efforts in the structural engineering community has shifted the focus from the development of ductile structures based on the conventional capacity design methodology and the seismic analysis of individual components of the infrastructure to the quantification of reliability, risk and resilience of entire distributed civil infrastructure systems and networks [5-7].

Occurrence of a large earthquake along the Nankai Trough is concerned in Japan and it is expected that the damage and the economic loss caused by seismic ground motion and cascading events are more severe than those caused by the previous large earthquakes [2]. In addition to the quantification of performance indicators, further studies on the contribution to risk reduction and resilience enhancement are needed. Recently, Honda et al. [8] proposed the anti-catastrophe concept which is defined as “the capacity of



a structure to prevent the occurrence of catastrophic situations as a single structure or system of various structures, even when it is exposed to a situation that is not considered in conventional design, which requires a procedure to verify that the response of the structure to the specified external force is within the prescribed range”.

In this paper, some lessons from the 2011 Great East Japan earthquake and the 2016 Kumamoto earthquake are presented. Then, considering the very high failure probability of structures in the regions where the effects of both seismic shaking and tsunami waves due to the anticipated Nankai Trough earthquake would be very intense, research studies on practical implementation of anti-catastrophe concept in terms of structural control and restoration are introduced based on the author's previous studies [2, 10, 11, 12]. For more information, please refer to them.

2. Lessons from recent large earthquakes in Japan

In Japan, seismic design specifications for structures and civil infrastructure systems have been significantly revised. The first seismic design code for road bridges, which included the seismic analysis considering the inelastic bridge behaviour and seismic design actions for the verification of the no-collapse requirement (i.e. Level 2 Ground Motion) was issued in Japan in 1990. Before 1990, the designers did not predict the whole behavior of bridges under seismic excitation and did not identify the most probable failure modes of these bridges [11]. Also, there was a lack of proper knowledge on structural details.

Figure 1 shows typical failure modes of RC columns designed according to the old design code. RC bridge piers had insufficient shear reinforcement and/or have cut-offs of longitudinal rebars without adequate anchorage length at the midpoint of bridge pier. These deficiencies caused several damages to RC columns during the past large earthquakes.



Fig. 1 – Typical failure mode of RC columns designed in the 1970s

Based on the experience of seismic damage to structures and research progress on earthquake resistance, shear and ductility design methodologies of RC components were modified. Figure 2 shows the relationship between horizontal load and displacement of a bridge pier. According to the revisions of seismic design codes, lateral strength and displacement ductility have been improved significantly.

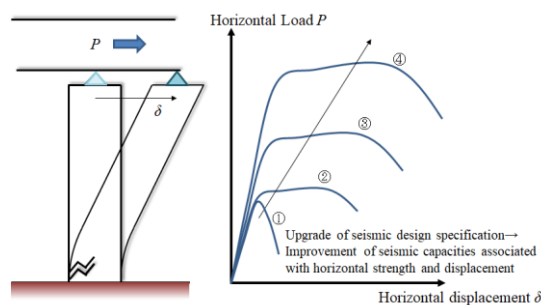


Fig. 2 – Improvement of seismic capacities associated with horizontal strength and displacement [2]



Several structures were severely damaged and collapsed not only due to the strong ground motion, but also to the subsequent tsunami, landslide or fault displacement. Figure 3 shows the bridge collapses due to the huge landslide during the 2008 Iwate-Miyagi Nairiku earthquake and the 2016 Kumamoto earthquake, and the giant tsunami during the 2011 Great East Japan earthquake.



Fig. 3 – Example of bridge collapses due to the subsequent events: (a) collapse due to the land slide during the 2008 Iwate-Miyagi earthquake; (b) collapse due to the tsunami during the 2011 Great East Japan earthquake; and (c) collapse due to the land slide during the 2016 Kumamoto earthquake

The effect of corrosion on the deterioration of the capacity of bridges under seismic hazard has to be considered (see Figure 4). It is important to understand that the seismic demand depends on the results of seismic hazard assessment, whereas the seismic capacity depends on the environmental stressors, such as hazard associated with airborne chlorides. The seismic performance of existing bridges in a harsh environment cannot be expected to be the same as that at the time of construction



Fig. 4 – Bridge components with material deterioration



Fig. 5 – Example of resilient structures against the catastrophic event: (a) rigid frame in the tsunami affected region taken after the 2011 Great East Japan earthquake; and (b) rigid frame in the landslide affected region taken after the 2016 Kumamoto earthquake

Compared with the conventional girder bridges, a rigid frame bridge under seismic action has less damage due to the effect of tsunami or landslide as shown in Figure 5. The rigid frame structure could be appropriate for the bridge if the hazards associated with tsunami and landslide have to be considered. Since



the rigid frame structures do not have bearings between the superstructure and substructure, they could prevent the washout of superstructure due to the tsunami attack compared with the conventional girder bridge. Figure 5 (b) shows that the abutment of Aso-Choyo bridge could not support the PC box girder after it was transversely displaced by the landslide. However, since both the superstructure and substructure were rigidly connected and behaved as a continuous unit, the severe damage to the Aso-Choyo bridge due to this landslide was not observed.



Fig. 6 – Temporary bridges constructed after the 2011 Great East Japan earthquake

Tsunami forces during the 2011 Great East Japan earthquake caused the collapse of a number of bridges that formed a vital link between towns in the Tohoku Region. Since this severely constrained post-earthquake disaster recovery, temporary bridges, as shown in Figure 6, have been constructed at several locations. These bridges were used for the evacuation of affected people and the transportation of emergency goods and materials. Constructing or retrofitting all structures with high-performance requirements that prevent any damage of failure due to strong ground motion and giant tsunami caused by the Nankai Trough earthquake would be too expensive and impractical. Preparing the temporary bridges before the occurrence of the catastrophic event could be an option for the resilience enhancement.

3. Progress of structural design and assessment methodologies

With the development of computer technology and computer simulation capability, and with the lessons from the disasters as described in Section 2, structural design methodology has progressed so that consequences caused by the structural failure and several performance indicators (i.e. risk, resilience and anti-catastrophe) under multiple hazards are being developed. Figure 7 shows the progress of structural design methodology from the deterministic allowable stress design toward the life-cycle-based design and assessment of transportation networks involving bridges [2].

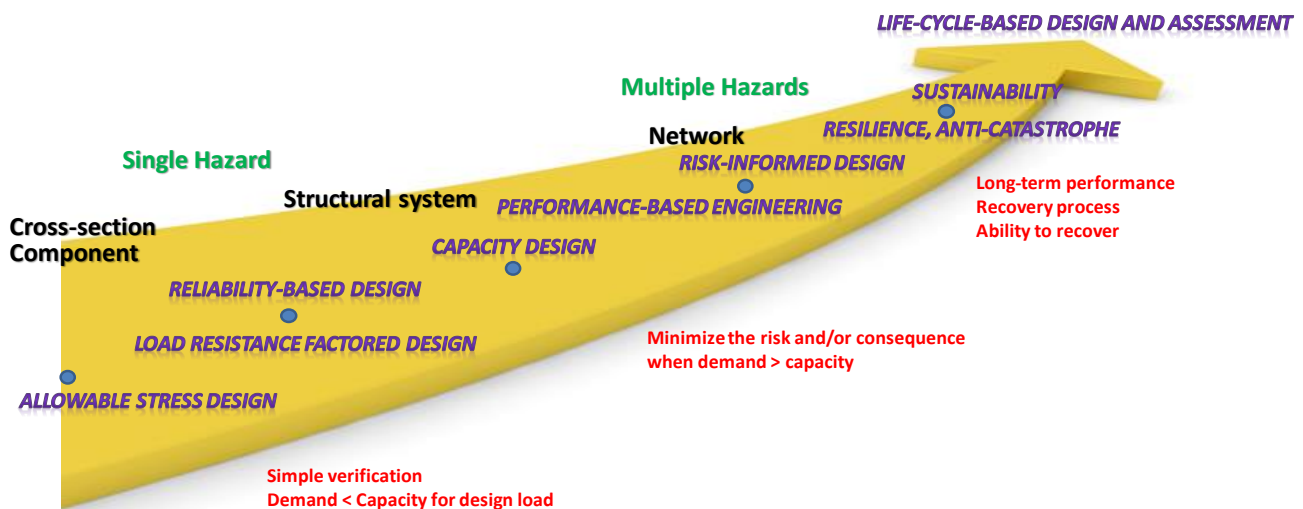


Fig. 7 – Progress of structural design methodology [2]



Evolution of structural design methodologies from allowable structural design (ASD) method to load and resistance factored design (LRFD) method has revealed the importance of uncertainty consideration in balancing economical and safety aspects of structural designs [13]. Along with the improvement of computer performance, R and L at the structure-level could be evaluated by the nonlinear and dynamic analysis considering uncertainties and correlations. A reliability-based capacity design procedure was proposed to obtain the hierarchy of resistance of the various structural components and failure modes necessary to ensure a suitable plastic mechanism and avoid brittle modes [11]. Although the capacity design method has been developed to maximize post-event operability and minimize the cost of repairing bridges after a severe earthquake, consequences associated with functionality and recovery cannot be explicitly incorporated in the reliability-based design method.

Performance-based engineering has gained significant attention and is being used in many areas of structural engineering. Performance-based earthquake engineering has been at the frontier among natural hazards [14]. This framework is based on the total probability theorem and can be disaggregated into different analysis phases that include hazard analysis, structural analysis, fragility analysis, and consequence estimation. When consequences are evaluated in terms of several measures, e.g., monetary loss, human fatalities, time to recover and environmental damage, risk, resilience and sustainability can be quantified. Recent studies in the literature investigating the risk, resilience and sustainability through quantitative approaches are summarized in [2].

4. Risk reduction and resilience enhancement in terms of structural control and restoration

It is expected that the damage and the economic loss resulting from the anticipated Nankai Trough earthquake and its associated tsunami would be larger than those resulting from the 2011 Great East Japan earthquake. Akiyama et al. [2] estimated the reliability, economic loss and recovery time of road networks involving bridges and embankments under seismic and tsunami hazards caused by the anticipated Nankai Trough earthquake. Figure 8 shows their tsunami propagation analysis [2]. The extensive seismic and tsunami hazard levels given the occurrence of the Nankai Trough earthquake can cause the severe risk. A countermeasure for such harsh hazards needs to be developed in terms of structural control and restoration.

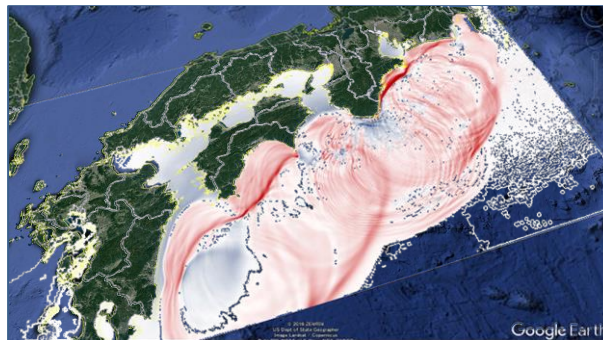


Fig. 8 – Tsunami propagation analysis of tsunami caused by the anticipated Nankai Trough earthquake [2]

In the seismic design and retrofit of bridges, it is necessary to confirm that (a) shear strength of a component must be larger than flexural strength to ensure the ductile behaviour; and (b) the lateral strength hierarchy between components induces the plastic hinge to the appropriate component [11]. Considering the accessibility of the plastic hinges for future inspection and repair, bridge pier can be selected as the energy-dissipating component. Figure 9 shows a capacity design methodology of a bridge structure.

Since it is important in the conventional capacity design to increase the seismic ductility capacity of bridge columns, studies on how to obtain the ductile behaviour of RC and steel columns have been conducted. If bridge structures are constructed on soft soil which has high potential of liquefaction in a severe earthquake, it is difficult to prevent damage to the pile foundation. To obtain the adequate hierarchy between the lateral strengths of bridge pier and pile foundation even in the soft soil, a prestressed reinforced concrete pile using high-strength concrete and rebars and carbon fiber sheets to increase the pile's flexural



capacity has been developed. Figure 10 shows an example of bridge component developments according to the conventional capacity design methodology.

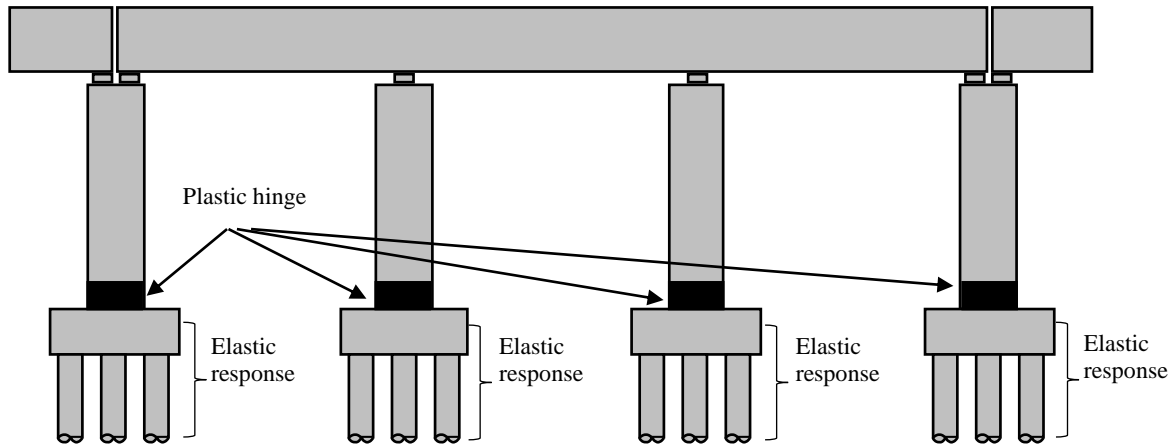


Fig. 9 – Capacity design methodology of bridge structures [9, 11]



Fig. 10 – Development of bridge components according to the capacity design methodology: (a) steel tube column with high displacement ductility; and (b) ultra-high-strength prestress concrete pile with carbon fiber sheet [9, 12]

The seismic technology to ensure the safety of structures and civil infrastructure systems for the current seismic design actions (i.e. actions for the verification of the no-collapse requirement) has been established. However, seismic intensity of the anticipated Nankai Trough earthquake could be much larger than that of the seismic design actions. In addition, although the bridge column designed according to the latest seismic code exhibited good ductile behavior during recent earthquakes, structures have endured severe damage and undesirable permanent residual displacements, indicating that their seismic resilience has not been ensured adequately. The need to repair structural damages after a strong earthquake has been regarded as an acceptable consequence in the capacity design methodology, although such repairs are sometimes not financially viable; moreover, structures would be demolished after strong earthquakes, leading to large economic losses. Undoubtedly, the disadvantages in the capacity design method provide evidence of the need to promote structural features that can perform elastically during stronger earthquakes, such as the anticipated Nankai Trough earthquake. Several interesting new technologies to ensure the seismic resilience in terms of structural control have been developed [2]. Figure 11 shows one example of a damage-free bridge using low-cost materials and 3D-printer which can ensure the seismic resilience after an extremely strong earthquake [10].

Seismic ground motions and subsequent tsunami and landslide due to the anticipated Nankai Tough earthquake would damage many structures simultaneously. To ensure the resilience of civil infrastructure systems, it is of vital importance to develop proactive measures to recover structures and civil infrastructure



systems. Palermo and Mashal [15] provides a bridge overview of ABC. Prefabrication of structural components using ABC technology can be a resilient solution. This decreases on-site construction time and helps roads and road structures reopen soon after a disaster [2]. It is necessary in the anticipated affecting region to develop a technology for making precast elements lighter, providing constructible beam-column and column-foundation connections and assembling the elements without heavy-construction-equipment. Figure 12 shows an example of a prefabrication of structural component using ABC technology.

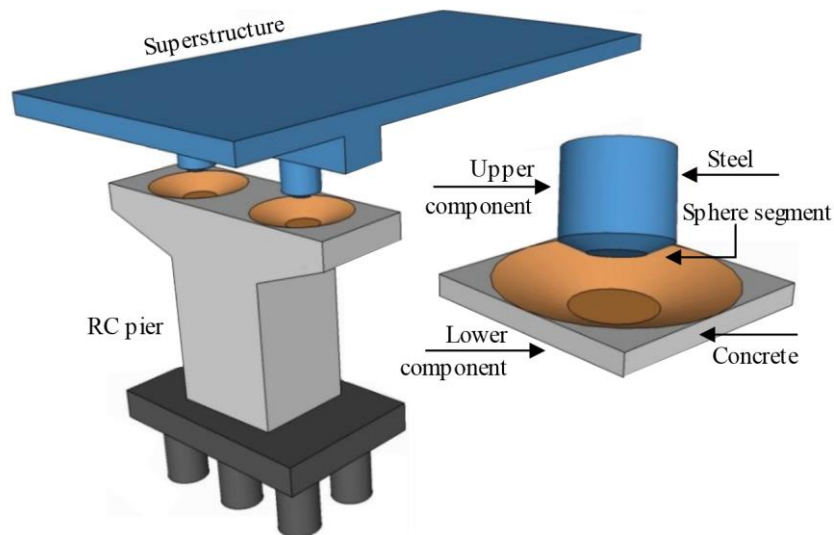


Fig. 11 – Development of low-cost sliding pendulum system [10]

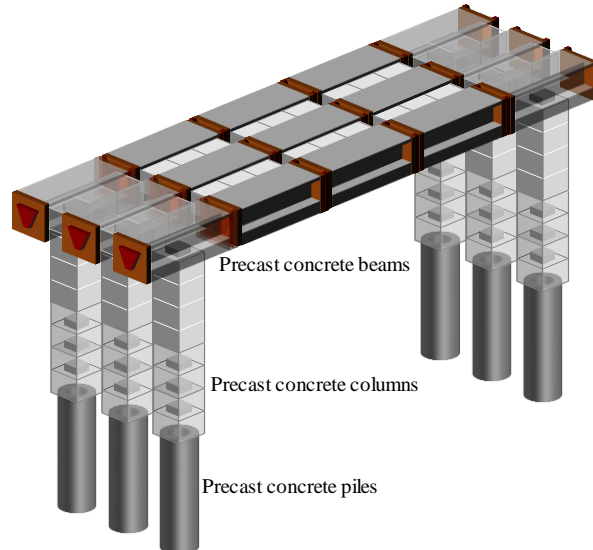


Fig. 12 –An example of a temporary bridge using precast concrete blocks [2]

5. Conclusions

To reduce the risk and enhance the resilience of civil infrastructure systems under extreme events, various efforts not only on the probabilistic quantification of risk and resilience of individual structure and network, but also on the developments of resilient structures and prefabrication of structural component for accelerated construction are required for implementation of anticatastrophe concept.

Structural engineers have to provide substantial contributions to risk reduction and resilience enhancement under natural hazards considering the very high failure probability of structures in the regions



where the effects of both seismic shaking and tsunami waves due to the anticipated Nakai Trough earthquake would be very intense.

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