Damage reduction countermeasures for short span bridges focusing on restorability of structural joints

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Abstract: Lying on one of the world's most active seismic faults, Japan faces the continuous threat of natural disasters. The earthquake that struck east Japan on 11 March 2011, and the devastating tsunami, raised many very serious questions about this country's land and its disaster prevention and disaster reduction strategies for resilience. Disaster-related losses cause short- as well as long-term adverse effects on economy, society, health, culture and the environment. In Japan, the events of 11 March 2011 highlighted the need for the related government agencies, municipalities, research organisations and universities to work together in formulating and implementing a holistic and comprehensive policy approach for damage reduction countermeasures. In this paper, damage reduction countermeasures for short span bridges are presented focusing on the restorability of structural joints, with a view to earthquakes, tsunamis, floods, and deterioration.

Keywords: bridge system; joints; damage reduction; earthquake; tsunami; flood; resilience; restorability; deterioration of bridges.

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1 Introduction

A historical earthquake of magnitude 9.0 occurred on the 11th of March in 2011. The earthquake was magnitude 9.0 (Mw) undersea megathrust earthquake off the coast of Japan, which is the largest earthquake ever recorded near Japan. The strong ground motion registered at the maximum 7 on the Japan Meteorological Agency seismic intensity scale. The hypocentral area of this earthquake extended from off-shore Iwate prefecture to off-shore Ibaraki prefecture where the length is about 450 km. It was confirmed that there were 15,897 deaths and 2,533 people missing until the first of March in 2019. The rupture area of the fault was approximately 450 km length by 200 km width. And it generated powerful tsunami waves which brought the disastrous destruction of coastal cities in Tohoku area. Most of the infrastructures were not critically damaged by the ground motion of earthquake itself, however, completely destroyed by the massive tsunami waves. In particular, some bridge superstructures were entirely washed away, and others remained with slight damages.

The events of 11 March 2011 highlighted the need for the related government agencies, municipalities, research organisations and universities to work together in formulating and implementing a holistic and comprehensive policy approach. A new era on disaster risk reduction has begun after the historical earthquake in Tohoku area including Sendai. The Sendai Framework for Disaster Risk Reduction 2015–2030 emphasised the importance of solid evidence and a scientific basis for risk-informed development and investment. It also highlighted the important linkages and mutual reinforcement for disaster risk reduction with the 2030 agendas: the sustainable development goals (SDGs), the Paris Agreement on Climate Change and the New Urban Agenda. The importance of a solid scientific base for risk-sensitive planning and decision-making and the critical role of science and technology has been pronounced more than ever before (Yoneda et al., 2015).

Global Forum on Science and Technology for Disaster Resilience 2017 was held in Tokyo from 23–25 November 2017 in which the following needs under the four priorities to be urgently addressed by our community were demonstrated (Global Forum, 2017).

1. We need to contribute to knowledge on disaster risk.
2. We need to contribute to strengthening disaster risk governance to reduce disaster risk.
3. We need to encourage investment in disaster risk reduction for resilience.
4. We need to promote 'build back better' in recovery, rehabilitation and reconstruction.

We should integrate different specialties and establish comprehensive and effective risk reduction countermeasures for local communities, considering each local environment and conditions (Yoda, 2017). We will improve public awareness (cost effective), which is one of the most important roles for disaster reduction. Pre-disaster countermeasure is effective in both human security and economic growth. In this paper, damage reduction countermeasures for short span bridges focusing on restorability of structural joints are presented in view of fail-safe design concept. The concept of fail-safe designs is extended here to include not only structural system but also structural joints that mitigate the harm caused by failure. The design assumption is that failure will eventually occur but when it does the system, components, or joints will fail in a safe manner.

2 Countermeasures against earthquakes

2.1 Historical perspectives

The typical example of earthquake occurred in Japan was the Kanto earthquake in 1923. The main cause of many casualties in the earthquake was reported as the fire of densely populated area and about 90% of the casualties were resulted from it. The Kanto earthquake initiated the provision of seismic design in Japan. Many steel bridges instead of timber bridges have been constructed after the Kanto earthquake in Tokyo metropolitan area. In these 90 years, we have experienced a number of earthquakes, which yielded pertinent revisions of seismic design in Japan.

Figure 1 The Kanto earthquake (1923) (see online version for colours)

Source: Courtesy of JSCE

The other typical example of inland direct strike type earthquake was the Hyougo-ken Nanbu earthquake in 1995. Magnitude scale was 7.3. The damages due to this disaster were beyond our imagination. The main cause of many casualties in the earthquake was reported as building collapse and crushed body with it and more than 80% of the casualties were resulted from it.

Girders were fallen in many bridges due to malfunction of unseating prevention devices associated with the collapse of substructures. Accordingly the Japanese specifications were revised to performance-based design methodology.

Figure 2 The Hyougo-ken Nanbu earthquake (1995) (see online version for colours)

Source: http://www.kiso.co.jp/tec/sokuho/eq/hogo/HYOGO.htm

The 2011 off the Pacific coast of Tohoku earthquake occurred on the 11th of March in 2011. Powerful tsunami waves were caused by this earthquake and destroyed the cities in coastal area of Tohoku region. The main cause of many casualties in the earthquake was reported as tsunami and about 90% of the casualties were resulted from it.

Figure 3 The 2011 off the Pacific coast of Tohoku earthquake (see online version for colours)

In the area whose seismic intensity was large, many bridges without damage could be found. This is due to the continuous amelioration of seismic design criteria in Japan.

Even if we shall confine damage reduction countermeasures in the field of bridges, there are a lot of countermeasures to enhance the potential of earthquake resistant capacity. Rigidly-connected girders and piers are examples to make bridge structures earthquake-resistant, as shown in Figure 4 (Japan Bridge Association, 2012). In this paper, in view of resilience, restorable rigid frame joints are proposed in order to keep the rigid frame restorable.

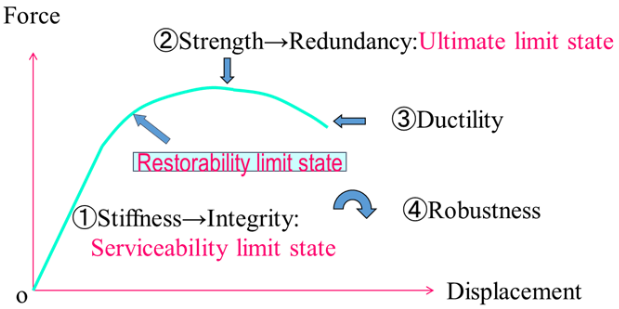
Figure 4 Hybrid rigid frame bridge (see online version for colours)

Source: Courtesy of JBA

2.2 *Restorable rigid frame joints against earthquakes*

Structures with necessary stiffness, sufficient strength, enough redundancy, high ductility, robust joint system, light weight and potential restorability are highly recommended in the aseismic design of bridges. As shown in Figure 5, restorability limit states are the states beyond which the structure can no longer be restored by repair using technologies available within reasonable ranges of cost and time.

Figure 5 Restorability limit state (see online version for colours)



Designing piers in such a way that failure cannot be catastrophic based on how failure will occur. The authors examined whether or not concrete filled tube (CFT) piers with slit will fail in a ductile manner, rather than brittle (Figure 6, Figure 7). It follows from this that robust joint system and potential restorability are expected to work well in the case of CFT piers with slit (Figure 8) (Waseda University, 2005).

Figure 6 Proposed restorable rigid frame joints (easy to repair) (see online version for colours)

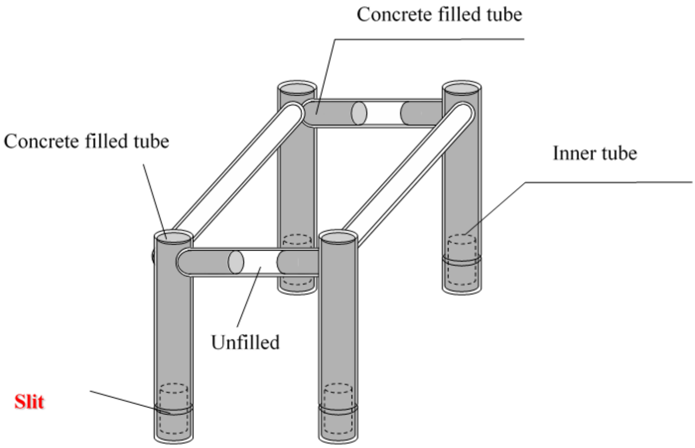
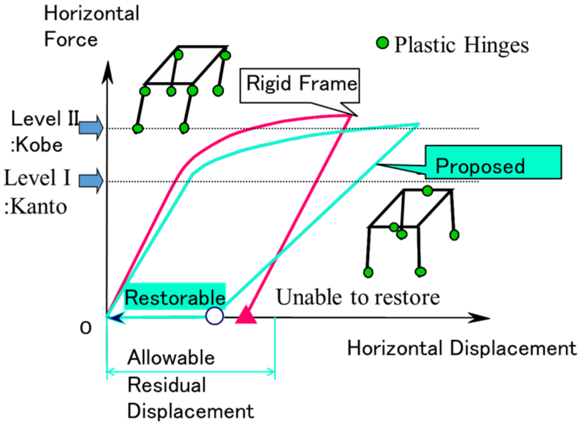
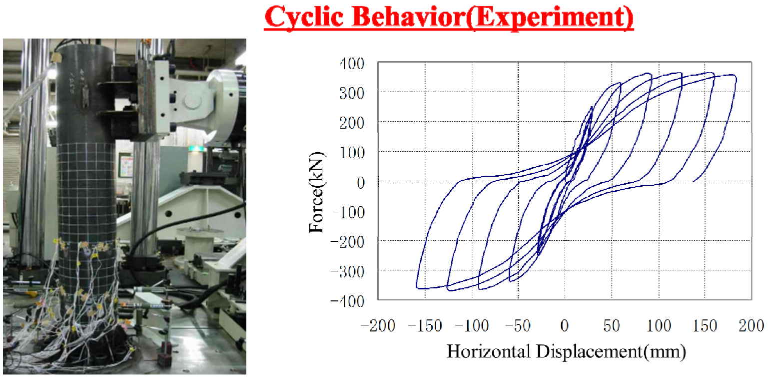


Figure 7 Restorable hybrid rigid frame (see online version for colours)



The authors have been working on several research and development projects concerning new types of structural joints. Such projects are focused on cost reduction, the improvement of aseismicity and maintainability, and mitigation of environmental impacts as well as restorability.

Figure 8 Cyclic behaviour of restorable hybrid rigid frame (see online version for colours)



3 Countermeasures against tsunamis

Bridge superstructures were swept away as shown in Figure 9, caused by the 2011 off the Pacific coast of Tohoku earthquake. And some bridges became deformed by collision such as floating ships on tsunami (Figure 10).

Figure 9 Bridge partially swept away (see online version for colours)

The current design criteria do not take into account properly the forces due to tsunamis. On the basis of scientific knowledge such as analyses of ancient documents and surveys of tsunami deposits and coastal topography, necessary revisions of earthquake and tsunami countermeasures are expected. As far as bridges are concerned, investigations of damage reduction countermeasures are ongoing projects in the field of bridge technology.

Figure 10 Ship collision damage (see online version for colours)

Figure 11 Tearing off of fall-off prevention devices (see online version for colours)

Fall-off prevention devices for steel bridges tore off by tsunami waves. The wave force of tsunami could easily tear off the connectors of fall-off prevention devices which are strong enough to carry the dead load of the bridge itself. Therefore, the fall-off prevention devices are almost useless to prevent the bridge from being washed away by the large tsunami waves. Furthermore, the floating debris could give additional impact load on the superstructure located near the surface of the tsunami waves under the actual condition (Kasano et al., 2012).

In view of the height of bridge superstructures, the bridge superstructures that were located in lower height from the ground level tend to withstand the tsunami waves. On the contrary, the bridge superstructures on the high piers are likely to be washed away when subjected to the tsunami waves.

Figure 12 Shin-kitakami Oohashi (see online version for colours)

Figure 13 Truss members being swept away (see online version for colours)

The phenomenon that the bridge superstructures with high clearance tends to be swept away by tsunami waves is opposite to the result brought by the equation currently used to estimate the wave force in Japan. Therefore, in order to confirm this phenomenon, the tsunami wave forces acting on a bridge deck should be examined. Some fundamental studies on the tsunami wave forces acting on a bridge have started since the 2004 Indian Ocean earthquake and tsunami (Murakami et al., 2009; Kataoka et al., 2006; Shoji et al., 2009). Generally the removal of a bridge deck is caused by the lateral wave force in conjunction with vertical force (Araki et al., 2010). However the detailed flow mechanism of tsunami waves has not been explained yet. It is an urgent issue to establish the tsunami force in the design of bridges (Maruyama et al., 2012). More than that, tsunami waves also carried debris including ships on their surface. Then, it is expected that the debris collided with a bridge superstructure and pushed it away. Therefore, if the bridge deck is located as high as the height of tsunami waves, the deck is subjected to not only the wave force but also the impact force of crashing debris (Iemura et al., 2005).

The specific required performance such as the allowed form of damage by giant tsunamis and methods of verifying this performance have not been established. Then methods of considering tsunami acting force, forms of damage considering restorability, and verification standards that can control the progress of damage are being studied (Tamakoshi et al., 2014).

Submersible bridges, retractable bridges, thrust bridges are prospective bridge type for damage reduction countermeasure against tsunami as long as structural joints are concerned.

4 Countermeasures against floods (timber bridge)

In this section, the authors will introduce Japanese traditional countermeasure against floods, which is closely related with intentional weak link and/or restorable structural joints. Such an easy to replace joint may be used to prevent damage difficult to repair.

The Kintaikyo Bridge over the Nishiki River at Iwakuni in Japan was originally constructed in 1673. The five-span wooden arch bridge is one of the most historically significant bridges not only in Japan but also in the world (Figure 14). Each span of the three central arches is 35.10 m, the total length being 193.3 m and the roadway being 5.0 m wide. Despite the bridge's unique five-span arch structure, which is designed to enhance durability, the bridge is vulnerable to natural disasters such as floods and earthquakes.

Figure 14 Kintaikyo Bridge as of 2009 (see online version for colours)

The Kintaikyo Bridge was washed away on 14 September 1950 (Figure 15), when the river's flow volume increased to 3,700 m^3 per second at the point of the bridge. This flow volume exceeded the bridge's designed flood control level of approximately 2,470 m^3 per second.

Figure 15 Loss of one pier before collapse (1950)

Source: Courtesy of Iwakuni City Economic Department

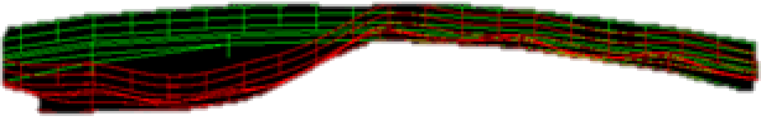
In 2005, typhoon 14, which was formed between the night of 6 September and the dawn of 7 September 2005, brought heavy rainfall (maximum precipitation: 59 mm/hour) over the upper reach of the Nishiki River. At the observing station situated 600 metres down-stream from the Kintaikyo Bridge, the water level reached 7.32 metres at 1:00 AM on 7 September, as compared to the danger level of 6.4 metres. The flow volume at that time was approximately 5,400 m^3 per second, which was much greater than the level recorded when the bridge was carried away in 1950. The typhoon 14 inflicted extensive damage on Kintaikyo Bridge. The drift from upper reaches destroyed two piers of the first span. This damage was very similar to the damage in 1950 (Iwakuni City Economic Department, 2007).

Despite the loss of the two piers from the first span, its superstructure remained intact (Figure 16). The superstructure was protected by the design of a special tenon called *hozo* which had been tapered to allow members disjoint easily, so that substructural damage would not impact the superstructure. In other words, the *hozo* was designed to function in a way similar to a fuse in an electric circuit and used to prevent damage to expensive or difficult to repair the superstructure. This unique damage reduction countermeasure is considered to be based on the fail-safe design concept which could manage the mitigating damage if failure occurs.

In order to confirm the validity of the unique damage reduction countermeasure, the numerical analyses using FEM were performed by the authors research group. The numerical results are shown in Figure 17 which demonstrates that the loss of two piers do not lead to the collapse of the superstructure. The maximum vertical displacement was 26 mm in the analysis, although the measured maximum vertical displacement was nearly 100 mm.

Figure 16 Loss of two piers reducing damages (2005) (see online version for colours)

Figure 17 Numerical study of damaged girder (2005) (see online version for colours)



5 Countermeasures against deterioration

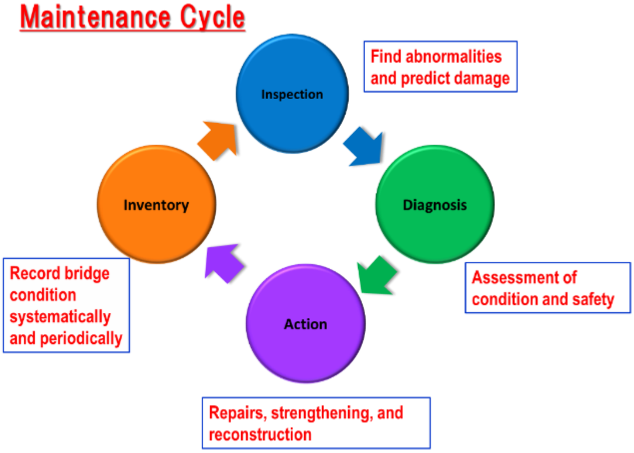
There are many facilities, although sound, do not have the basic physical capacity due to underestimation at the design stage. However, in view of the intensification of effects such as the frequent occurrence of earthquakes and the increase in torrential rainfall in recent times, this situation is far from ideal in Japan. Examinations of physical capacity and urgent improvements thereto are indispensable. The health reports for various infrastructure are scheduled to be released every five years in Japan (JSCE, 2017).

Maintenance of infrastructure consists of three factors, namely:

1. A system to carry out maintenance, adequate inspections, diagnosis and measures to implement it.
2. Development of an effective and efficient maintenance technique.
3. Budgetary provisions. If there were deficiencies in any of the above factors, maintenance cannot be adequately carried out.

Regarding an adequate system and implementation, administrators must acknowledge that strict demands as to public safety (injure to third person) will be placed on their managerial responsibilities and capable engineers must be assigned who can adequately determine the deterioration state of the infrastructure and the countermeasures thereof.

Figure 18 Maintenance cycle of bridges (see online version for colours)



Source: RAIMS (2019)

As to maintenance technology, new techniques need to be adequately evaluated and an arrangement and contract system to promote their use are required. Advancements in non-destructive inspections are remarkable; therefore, it is indispensable to promote the streamlining of standards and systems based on latest technologies and inspection data (RAIMS, 2019). Requirements for the amelioration of resilient systems are often said to be the ability of anticipating, monitoring, responding, learning (including AI). These requirements are directly related with inspection, diagnosis, action, inventory, in the maintenance cycle (Figure 18).

On the contrary, concerning budgetary provisions, it is necessary to have the basic understanding that deterioration of infrastructure leads to social insecurity and economic stagnation. Maintenance entails an accumulation of daily effort, and administrators need to secure a long-term stable budget. A system design in which there is a sound growth in maintenance businesses is essential (JSCE, 2017).

In general, the performance-based design specifies the performances required for structures (required performances) and verification of whether or not the required performances are satisfied, by using the appropriate verification indices. Therefore, the important thing is what required performances are to be set for the structures, which leads to the features of the design standard. The safety and serviceability are performances common to almost all the standards while others are roughly classified into the durability, restorability, environmental compatibility, constructability and maintainability, and economy, although such classifications are not universally employed in standards. The performance-based design system of steel and composite structures of the Japan Society of Civil Engineers (JSCE) (JSCE, 2007) is characterised by Figure 19 and Table 1.

The present standard specification describes only the currently applicable review method for this performance, but will be positioned as the required performance so that the quantitative verification method can be applied according to the prospective technical progresses. ‘Constructability’ represents the performance required during construction, such as safety at construction, easiness of fabrication and erection, and easiness of quality control. This is an important performance to be taken into account of deterioration. In this respect, the constructability was selected as one of the required performances in the design specification. 'Maintainability' represents the easiness of maintenance of structures, which is now under developing stage.

'Restorability' which is closely related with the fail-safe designs represents the easiness with which the performance can be restored in case of performance deterioration due to structural damage caused by expected actions (mainly the influence of earthquake). The easiness of performance restoration in case of damage during normal action leads to that of maintenance, so that this is to be handled as the performance item, keeping in mind the resilient infrastructure. Fail-safe designs involve a testing and analysis to estimate how long the structure and/or component can be in service before it will likely fail. If failure would be expensive or even life threatening, then a larger factor of safety is justified.

Figure 19 Conceptual view of required performances (see online version for colours)

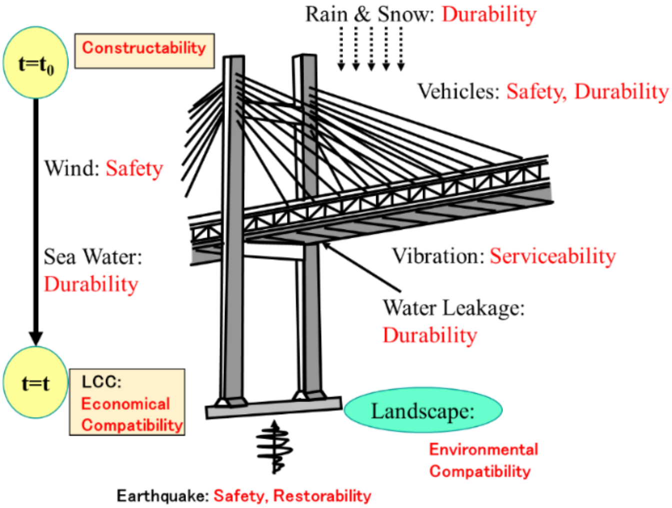
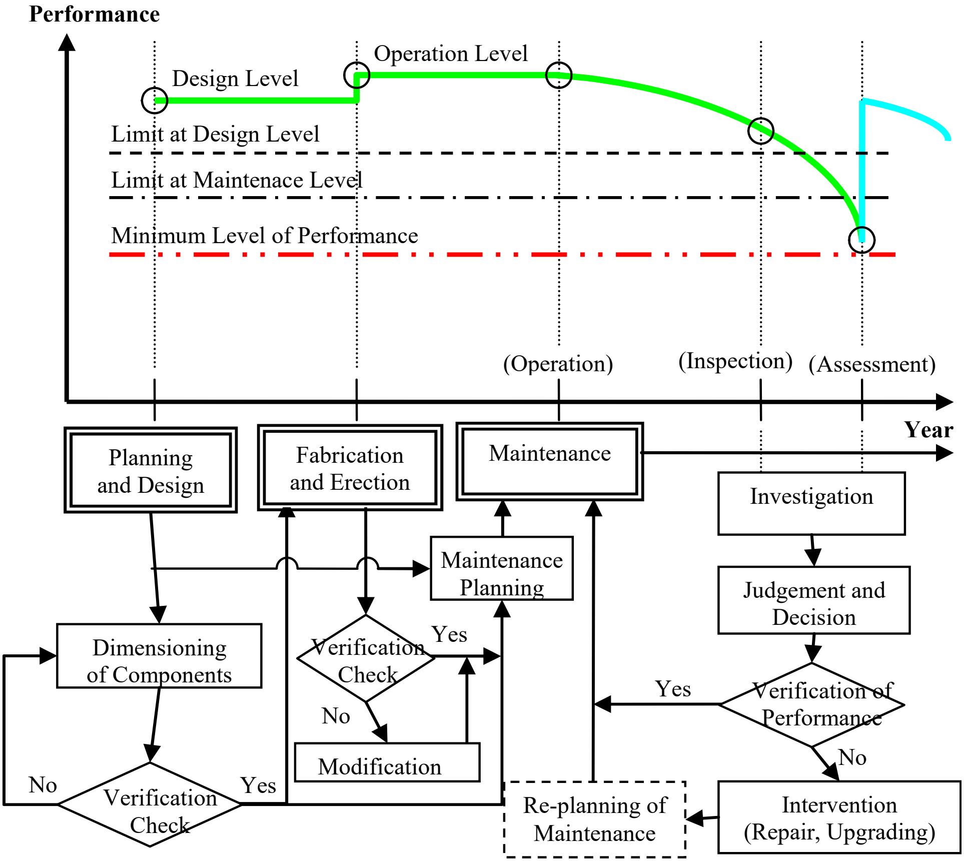


Table 1 Required performances in design

Required performance	*Performance item*	*Limit state*
Safety	Safety of structure (ultimate, stable)	Ultimate
	Public safety (injury to third party)	
	Earthquake (ultimate, stable)	
	Constructability (ultimate, stable, integrity)	
Serviceability	Running, walking	Serviceability
	Durability (fatigue, damage, corrosion)	
Restorability	Recovery from earthquake damage	Restorability
	Maintainability	
Social and environmental compatibility	Social importance	Optimization
	Economical compatibility (LCC, LCU)	
	Environmental compatibility (noise, vibration, landscape, LCA)	

The newly published design specification contains some significant steps forward in codified performance-based design, but there are still many unsatisfactory aspects of codified design that need to be improved. We expect to see significant improvements in the performance-based design for maintenance formulated in terms of design life time as shown in Figure 20. Disaster preparedness and response are long-term issues. Benefits of fail-safe designs include being able to manage the unexpected and mitigating damage if failure occurs in the bridge system and structural joints.

Figure 20 Life cycle of performance level (see online version for colours)



6 Concluding remarks

1 Although the largest-possible mega earthquakes and tsunamis might be considered from every possible aspect, damage reduction countermeasures should be examined from the view point of the protection of peoples' lives as the first priority. Damage reduction countermeasures for short span bridges focusing on restorability of structural joints are considered to be one of the promising method to keep the bridges resilient.

2 As far as bridges are concerned, the potential application of technical investigation on the damage reduction countermeasures for earthquakes, tsunamis, floods and deterioration will certainly depend on both national and international research and development programs. Therefore, national and international platforms for more effective use of disaster prevention and disaster reduction strategies for resilience will be hoped for, with a view to long-term preparedness and awareness of the community against disasters.

3 Concept of disaster risk reduction for resiliency is different in different countries, the unified and definite concepts of resiliency specification in bridge design should be improved.

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