# Numerical Investigation of Residual Strength Capacities of Steel Bridge Members under Earthquake Loading

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## 1. Introduction

Many existing bridges in Japan are suffering from damage due to deterioration of materials, fatigue cracks in RC slabs, steel decks and steel members due to the passage of many overweight vehicles, much heavier than those specified in bridge design specifications, and so on (Kitada, 2006). With aging, corrosion becomes one of the major causes of deterioration of steel bridges, and their damages seriously affect their durability. Due to economic constraints, it is not possible to conduct tests for each and every aged bridge structure within their bridge budgets. Therefore, nowadays, use of numerical analysis method could be considered to have a reliable estimation in bridge maintenance industry (Kaita, 2008).

Furthermore, recent earthquakes demonstrated the potential seismic vulnerability of some types of steel bridges. Especially during the Great Hanshin Earthquake of January 17, 1995, steel bridge structures suffered various kinds of damages which they never experienced before (Miki, 2005). Corrosion and its effects can trigger the damages caused by earthquakes and it would be vital to understand the behavior of existing steel bridges which are corroding for decades in future severe seismic events as well. This paper proposes a simple and reliable methodology to estimate the remaining seismic strength capacities of corroded steel members, which can be used to make rational decisions about the maintenance management plan of steel infrastructures.

## 2. Corroded Test Specimen and Classification

A steel girder bridge of Ananai River in Kochi prefecture on the shoreline of the Pacific Ocean, which had been used for about hundred years, was used for this study. Many severe corrosion damages distributed all over the girder, especially, large corrosion pits or locally-corroded portions were observed on upper flanges and its cover plates. As it is necessary to categorize the different corrosion conditions into few general types for better understanding of their remaining strength capacities, 3 different types of corrosion levels were identified according to their severity of corrosion and they are classified accordingly as follows:

$\mu > 0.75$ ; Minor Corrosion
$0.75 \geq \mu \geq 0.5$ ; Moderate Corrosion
$\mu < 0.5$ ; Severe Corrosion

Here, the minimum thickness ratio (μ) is defined as:

$$\mu = \frac{t_{min}}{t_0} \qquad (1)$$

## 3. Dynamic Analysis

### 3.1 Seismic Analysis with Historical Earthquakes

In this study, three major historical earthquake records were used to understand the dynamic response of Ananai River Bridge in Kochi prefecture, Japan. The seismic analyses were performed considering the earthquake excitations caused by; 1995 Kobe earthquake (Mw=6.9), 1989 Loma Prieta earthquake (Mw=6.9) and 1940 El-Centro earthquake (Mw=7.1). The seismic response analysis is performed in two distinct stages. A natural frequency analysis is performed first. This is used to calculate the first 100 (or more; until more than 90% of total mass participation occurs) natural modes of vibration of the structure. The second phase of the analysis utilizes the IMDPlus option which performs enhanced time domain solutions using Interactive Modal Dynamics (IMD). In the IMDPlus solution, the structure is subjected to a support condition excitation governed by time histories of acceleration in the model global axes. In this example, the seismic excitation is applied directly to the bases of the structure using the first 40 seconds of each earthquake.

### 3.2 Results of Primary Seismic Analysis

The primary seismic analysis was performed with the three historical earthquakes as described above and the behavior of the structure was studied. In each analysis, critical members were identified considering the whole excitations of the corresponding earthquake records. It was noticed that, even though the main steel girders are well behaved due to earthquake loading, cross girder members were deformed in transverse direction. One example of the ultimate stress distribution of the bridge structure and the displacement history obtained for the critical member for the seismic analysis of 1995 Kobe earthquake is shown in Figure 1.

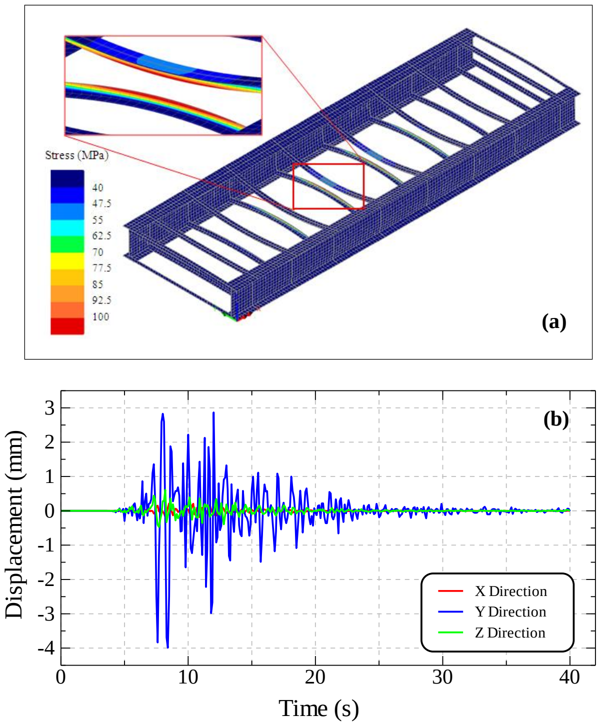


Figure 1: (a) Ultimate stress distribution of steel girder and (b) displacement histories of the critical member

### 3.3 Analytical Models of Secondary Seismic Analysis

In this study, five different analytical models were developed, in order to understand the seismic strength deterioration with the severity of corrosion condition. Here, the seismic model SM-1 with μ=1 represents the model without corrosion and used as the standard model in this analysis to compare with other SM models. The different corrosion conditions were adopted by using different minimum thickness ratio (μ) values and the details of those analytical models which are considered for this parametric study are shown in Table 1. The initial thickness ($t_0$) of the different seismic models (SM) was considered as 10.5mm. Furthermore, these analytical models were developed with the CCM parameters defined by Ohga *et al.* (2011) with different corrosion conditions. Here, the maximum corroded pit was modeled with the representative diameter ($D^*$) which could account the stress concentration effect and the material loss due to corrosion was considered by using the representative average thickness parameter ($t^*_{avg}$).

Table 1: Details of analytical models

| Model | μ ($t_{min}/t_0$) | $t_{c,max}$ (mm) | $D^*$ (mm) | $t^*_{avg}$ (mm) |
|---|---|---|---|---|
| SM-1 | 1.0 | 0.0 | 0.0 | 10.5 |
| SM-2 | 0.75 | 2.63 | 13.65 | 9.98 |
| SM-3 | 0.50 | 5.25 | 27.30 | 9.45 |
| SM-4 | 0.25 | 7.88 | 40.95 | 8.93 |
| SM-5 | 0.05 | 9.98 | 51.87 | 8.51 |

### 3.4 Secondary Seismic Analysis Results and Discussion

Figure 2 shows the load-displacement curves obtained for the analysis of Kobe earthquake for each seismic model. They clearly show that the dynamic behavior of each model was affected by different corrosion conditions. Further, it was noted that their residual strengths were significantly affected by the different levels of corrosion conditions attributed to each SM model.

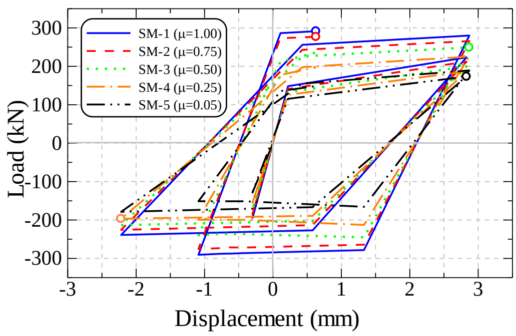


Figure 2: Displacement histories of the critical member during 1995, Kobe earthquake

Figures 3(a) and 3(b) show the percentage seismic strength reductions (%SSR) in yield and ultimate strength states of each SM model respectively. It was found that the %SSR in yield and ultimate states are non-linearly increased with increase of corrosion levels. The remaining yield and ultimate seismic strength capacities are decreased with the severity of corrosion condition for all three

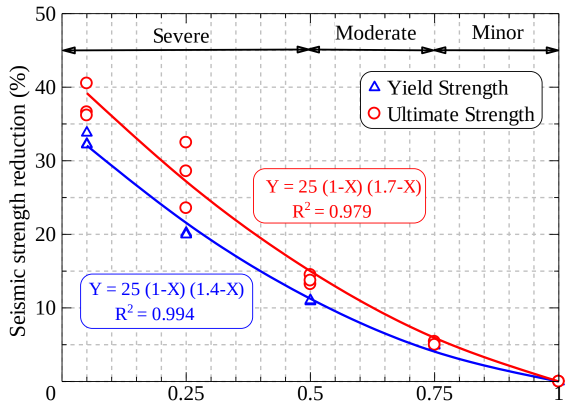


Figure 3: Relationship of percentage yield & ultimate seismic strength reduction vs. minimum thickness ratio (μ)

different earthquake loading histories. Furthermore, these results divulged that having a corrosion pit of minimum thickness ratio μ=0.05, could reduce up to 30% ~ 40% of its' original yield and ultimate strengths respectively. By considering Fig. 3(a) and 3(b), two equations for estimating remaining yield and ultimate seismic strength capacities can be derived as:

$$\%SSR_{yield} = 25\,(1-\mu)\,(1.4-\mu) \quad (2)$$

$$\%SSR_{ultimate} = 25\,(1-\mu)\,(1.7-\mu) \quad (3)$$

As the proposed strength reduction equations only requires the measurement of minimum thickness ratio, μ, which is an easily measurable parameter, this method can be used as a simple and reliable method to predict the yield and ultimate seismic behaviours of corroded steel members more easily and precisely.

### 5. Conclusions

The main conclusions of this study are:

1. Corrosion and its stress concentration effect will trigger the damages significant due to earthquake loading and hence they could even lead to the collapse of total structure.
2. Two very good relationships can be obtained for remaining yield and ultimate seismic strength capacities with high accuracy.

This method is simple and hence can be used for the maintenance management of steel bridge infrastructures with better accuracy.

### References

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