Role of Corrosion & Earthquakes on Degradation of Dynamic Behaviour of Steel Bridge Plates

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***Abstract*-Major steel bridges are usually the crucial elements of the road and railway infrastructures. Very often they constitute a part of critical links between highly habited areas. As a consequence, their closure or traffic capacity reduction causes major inconveniences for the users and result in significant losses to the economy. Corrosion is one of the most important causes of deterioration of steel girder bridges which affects their long term mechanical performance, usability, and durability. Furthermore, some recent earthquakes demonstrated the potential seismic vulnerability of some types of steel bridges, and hence, it would be very important to understand the behaviour of existing steel bridges which are corroding for decades in future severe seismic events as well. Therefore, there is a need for evaluation procedures for an accurate prediction of the load carrying capacity and seismic resistance of bridge structures, in order to make rational decisions about repair, rehabilitation, and expected life-cycle costs. Therefore this paper investigates the effect of severe corrosion on remaining seismic strength capacities of existing steel bridge infrastructures through many finite element analyses and develops a simple, accurate, and reliable methodology which can be used for their maintenance management plan.**

Keywords- Bridge Maintenance; Corrosion; Earthquakes; Seismic Resistance; Numerical Analysis

I. INTRODUCTION

Civil infrastructure systems are prone to age related deterioration due to the exposure to aggressive environmental conditions and inadequate maintenance, and often causes reduction of their carrying capacities. Designing these systems for a particular service life and maintaining them in a safe condition during their entire service life have been recognized as very critical issues worldwide. There have been many damage examples of older steel bridge structures due to corrosion around the world during past few decades and they intensified the importance of attention to the careful evaluation of existing structures for the feasibility of current usage and strengthening them by retrofitting some selected corroded members to ensure the public safety. In Japan, there are more than 50,000 steel railway bridges, where more than half of them have been used over sixty years and some bridges are aged over 100 years [1]. With aging and corrosion become one of the major causes of deterioration of steel bridges, and its damages seriously affect on the durability of steel bridges [2 and 3]. It is known that the corrosion wastage and stress concentration caused by the surface irregularity of the corroded steel plates influence the remaining strength of corroded steel plates [4]. In the future, it is evident that serious social problems will arise when the number of damaged bridges increases, as it is very difficult to retrofit or rebuild those aged bridges at the same time. Therefore, it is important to evaluate the remaining strength capacities of those bridges, in order to keep them in-service until they required necessary retrofit or rebuild in appropriate time.

Benefits of regular and proper inspections of older bridges cannot be overlooked. They not only help in planning the necessary work but also help in discovering and monitoring any problems, thereby reducing expensive maintenance, reducing operating hazards, preventing structural failures and averting emergencies. Therefore, no laxness in inspections should be permitted as they form the essential source of information to carry out a comprehensive evaluation of its current capacity. Several experimental studies of corroded surfaces were done by some researchers during past few decades, in order to introduce methods of estimating the remaining strength capacities of corroded steel plates [5-8]. But, to develop a more reliable strength estimation technique, only experimental approach is not enough as actual corroded surfaces are different from each other. Further, 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 infrastructure maintenance industry [9].

Previous studies, available numerical methods, and empirical equations developed by various authors require conducting detailed corroded surface measurements and the measurement of average thickness (t_{avg}) and/or the minimum average thickness (t_{avg_min}), in order to develop the respective analytical models and predict their yield and ultimate behaviours. Since the number of steel railway and highway bridge infrastructures in the world is steadily increasing as a result of new construction and extending the life of older structures, it becomes an exigent task to measure several thousands of points, to accurately reproduce the corroded surface by numerical methods and to predict the behaviour of that corroded member more precisely. So, it is vital to develop a rapid and accurate assessment method for the maintenance management of steel infrastructures. Ohga *et al*. [10] developed a simple, accurate and rapid analytical model which can be used to estimate the remaining strength capacities of actual corroded members more precisely, by measuring only the maximum corroded depth ($t_{c,max}$) and validated with many experimental results of corroded steel plates with different corrosion conditions.

II. SCOPE OF THE STUDY

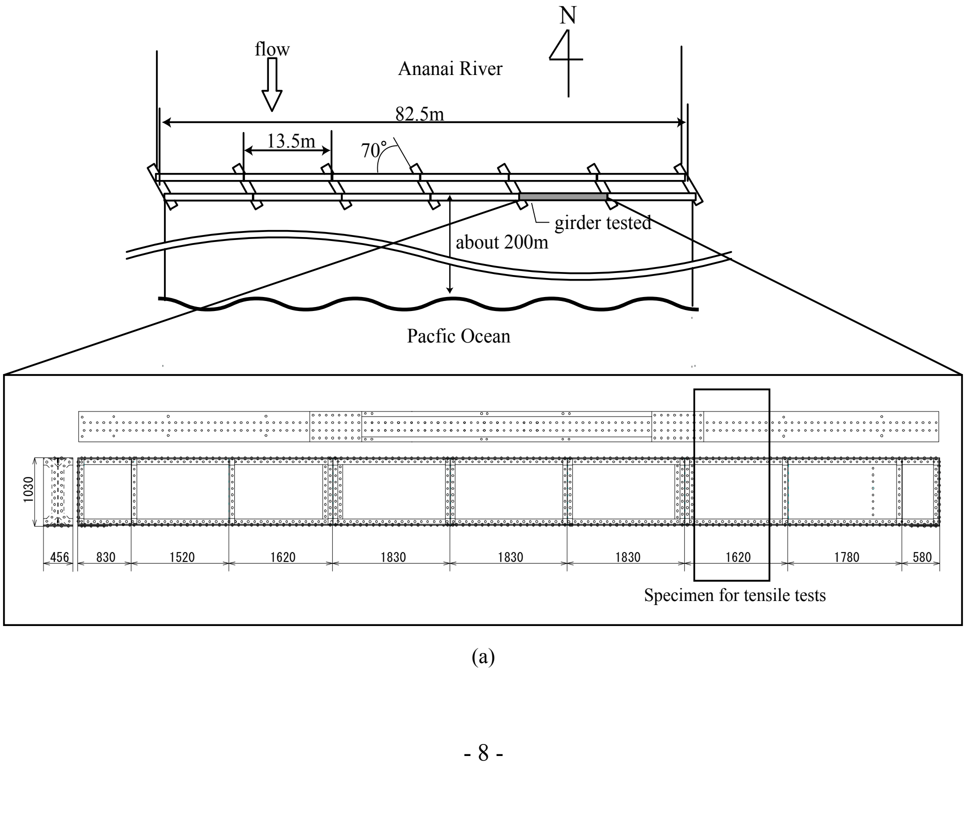
Recent worldwide severe earthquakes have shown that steel bridges can be vulnerable. Earthquake damage to a bridge can have severe consequences. Especially during the Great Hanshin Earthquake of January 17, 1995, steel bridge structures suffered various kinds of damages that they never experienced before [11]. Jiao *et al.* [12] also mentioned that a great deal of beam damage due to brittle fracture was observed in many steel bridge infrastructures due to the Kobe earthquake in 1995. In addition, there were many collapse, buckling, fracture, and cracking occurred in many steel infrastructures. All of these accidents were far more severe than contemplated in the conventional seismic design method and might essentially invalidate historical seismic design approaches and code provisions. Furthermore, many collapses, superstructure failures, and joint failures were observed in San Francisco due to the Loma Prieta Earthquake on October 17, 1989 [13]. Therefore, it is evident that, even though most of the steel bridge structures perform well with their specific energy dissipation characteristics, the failure risk associated with severe corrosion under mega earthquake events could not be underestimated.

Despite these uncertainties and variations, one can learn from past earthquake damages, because many types of damages occur repeatedly. By being aware of typical vulnerabilities that bridges have experienced, it is possible to gain insight into structural behaviour and to identify potential weaknesses in existing and new bridges. Historically observed damage has provided the impetus for many improvements in earthquake engineering codes and practice. Although there is no published information on the seismic performance of severely corroded members, practicing engineers have apparently not questioned whether rusted members can still exhibit the dynamic behaviour and hysteretic energy dissipation capacity commonly relied on for seismic resistance [14]. Therefore this paper investigate the effect of corrosion damage on remaining dynamic behaviour of existing steel bridge infrastructures and presents a simple, accurate and reliable methodology to estimate residual seismic strength capacities of corroded steel plates.

III. CORRODED TEST SPECIMENS

A. Test Specimen Configuration and Material Properties

The test specimens were cut out from the portion adjacent to end support of a plate girder of Ananai River Bridge in Kochi Prefecture on the shoreline of the Pacific Ocean [Fig. 1(a)], which had been used for about 100 years. This bridge had simply supported steel plate girders with six spans, with each of 13.5m. All plate girders were exposed to high airborne salt environment by strong sea wind for a long time. It was constructed as a railway bridge in 1900, and in 1975 changed to a pedestrian bridge, when the reinforced concrete slab was cast on main girders. The bridge was dismantled due to serious corrosion damage in year 2001. Twenty-one flange specimens (F1-F21) and five web specimens (W1-W5) were fabricated from the cover plate on upper flange and web plate respectively. Here, the flange and web specimens have the widths ranged from 70-80mm and 170-180mm respectively. Test specimen configuration is shown in Fig. 1(b). In addition, four corrosion-free specimens (JIS5 type) were made; each two from the flange and web, and the tensile tests were carried out in order to clarify the material properties of test specimens. The material properties obtained from these tests are shown in Table I.



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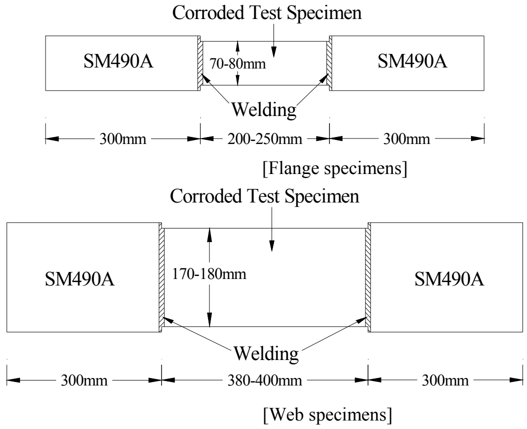


(b)

Fig. 1 (a) Location of the plate girder and (b) specimen configuration

TABLE I MATERIAL PROPERTIES

Specimen	Elastic Modulus /(Gpa)	Poisson's Ratio	Yield Stress /(Mpa)	Tensile Strength /(Mpa)	Elongation at Breaking /(%)
Corrosion-free Plate (Flange)	187.8	0.271	281.6	431.3	40.19
Corrosion-free Plate (Web)	195.4	0.281	307.8	463.5	32.87
SS400 JIS	200.0	0.300	245~	400~510	–

B. Corroded Surface Measurement

Accuracy and convenience are highly demanded in the measurement of corrosion surface irregularities. Furthermore, portability, good operability, and lightness would be imperative for choosing of a measurement device for on-site measurements. Therefore, the portable 3-dimentional scanning system, which can measure the 3-dimentional coordinate values at any arbitrary point on the corrosion surface directly and continuously, was used for the measurement of surface irregularities of test specimens. Here, the thickness of the corroded surface can be calculated easily from those measured coordinates.

The measuring device has three arms and six rotational joints, and can measure the coordinates of a point on steel surface by using the non-contact scanning probe (laser line probe). The condition of thickness measurement is shown in Fig. 2.

Fig. 2 Condition of thickness measurement

So, the thicknesses of all scratched specimens were measured by using this 3D laser scanning device and the coordinate data was obtained in a grid of 0.5mm intervals in both X and Y directions. Then, the remaining thicknesses of all grid points were calculated by using the difference of the coordinate values of both sides of those corroded specimens. Then, the statistical thickness parameters such as average thickness (t_{avg}), minimum thickness (t_{min}), standard deviation of thickness (σ_{st}) and coefficient of variability (CV) were calculated from the measurement results.

C. Corrosion Levels Classification

As it is necessary to categorize different corrosion conditions which can be seen in actual steel structures, into few general types, three different types of corrosion levels were classified according to minimum thickness ratio, μ (minimum thickness / initial thickness), in this study. The corrosion conditions with the minimum thickness ratio, $\mu > 0.75$ are defined as *minor corrosion*. And the *moderate corrosion* type is defined when the minimum thickness ratio, $0.75 \geq \mu \geq 0.5$. Further, the 3rd corrosion type with the minimum thickness ratio, $\mu < 0.5$ is defined as *severe corrosion* [8]. There, the initial thickness (t_0) of flange specimens and web specimens are 10.5mm and10.0mm respectively. Three specimens with F-14, F-13 and F-19 with minor, moderate and severe corrosion conditions respectively are shown in Fig.3. Furthermore, Fig.4 shows the relationship between the nominal ultimate stress ratio (σ_{bn}/σ_b) and the minimum thickness ratio (μ), where σ_{bn} is the nominal ultimate stress and σ_b is the ultimate stress of corrosion-free plate.

D. Tensile Test Results

Tensile loading tests were carried out at constant velocity under loading control by using a hydraulic loading test machine (maximum load: 2940kN) for all twenty-six specimens with different corrosion conditions. The loading velocity was set to 200N/sec for minor corroded specimens and 150N/sec for moderate and severe corroded specimens. Fig. 5 shows the load-displacement curves for three corroded specimens (F-14, F-13 and F-19) with three corrosion types.

Herein, the specimen (F-14) with minor corrosion has almost same mechanical properties (such as apparent yield strength and load-displacement behaviour etc.) as the corrosion-free specimen. On the other hand, the moderate corroded specimen (F-13) and the severe corroded specimen (F-19) show obscure yield strength and the elongation of the specimen F-19 decreases notably. The reason for this is believed to be that the local section with a small cross-sectional area yields at an early load stage because of the stress concentration due to irregularity of corroded steel plate. And this will lead moderate and severe corroded members to elongate locally and reach the breaking point.

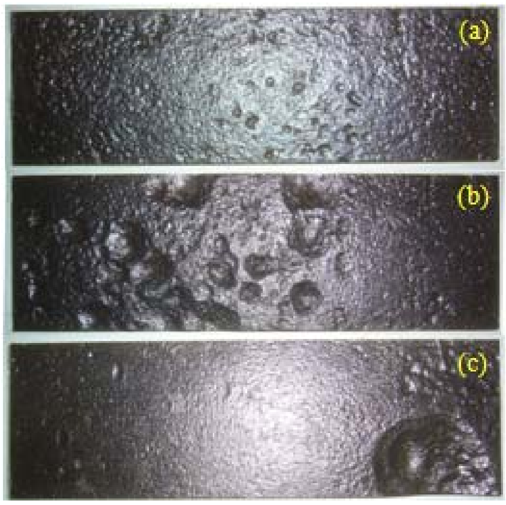


Fig. 3 Plates with (a) minor corrosion (F-14); (b) moderate corrosion (F-13) and (c) severe corrosion (F-19)

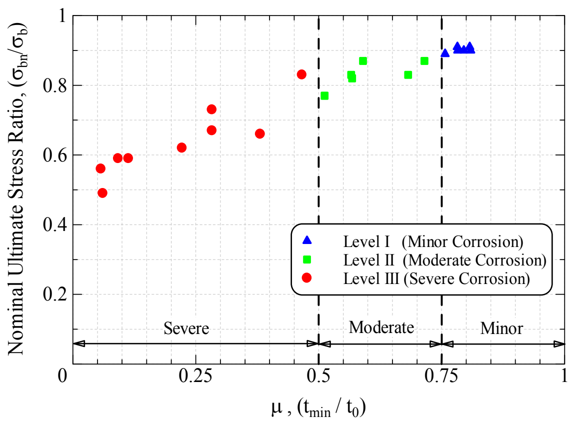


Fig. 4 Relationship of ultimate stress ratio & μ

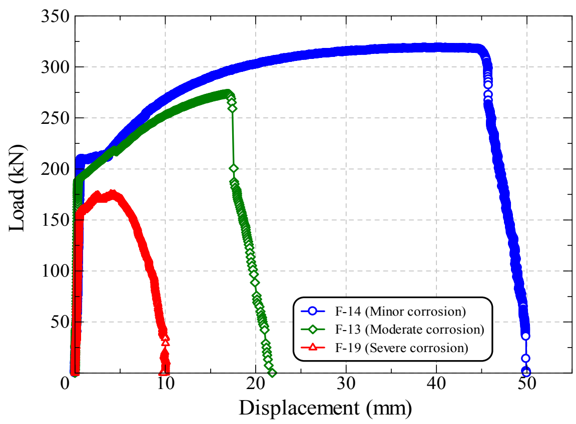


Fig. 5 Experimental load-displacement curves

IV. DYNAMIC ANALYSIS

A. Primary 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 (M_w=6.9), 1989 Loma Prieta earthquake (M_w=6.9) and 1940 El-Centro earthquake (M_w=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 eigenvalues (frequencies) and eigenvectors (mode shapes) are stored and used in the subsequent IMDPlus analysis. 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 forty seconds of each earthquake.

B. Results of Primary Seismic Analysis

The primary seismic analysis was performed with three historical earthquakes as described above and the behaviour 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 were well behaved during the earthquake loading, cross girder members were deformed in transverse direction. One example of the ultimate stress distribution of the bridge structure during the seismic analysis of 1995 Kobe earthquake is shown in Fig.6. Further, Fig.7 shows the displacement histories of the critical member, obtained from the seismic analysis of the structure for each earthquake.

C. Analytical Models of Secondary Seismic Analysis

Five different analytical models were developed and analysed with the same modelling features, analytical procedure, 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 Ⅱ. The initial thickness (t_0) of different seismic models (SM) was considered as 10.5mm. Furthermore, these analytical models were developed with the CCM parameters defined by Ohga *et al.* [10] with different corrosion conditions. Here, the maximum corroded pit was modelled 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}).

The 3D iso-parametric hexahedral solid element with eight nodal points (HX8M) and updated Lagrangian method based on incremental theory were adopted in these analyses. Nonlinear elastic-plastic material, Newton-Raphson flow rule, and Von Mises yield criterion were assumed for material properties. The *Stress Modified Critical Strain Model (SMCS)*, which was proposed by Kavinde *et al.* [15] to evaluate the initiation of fracture as a function of multiaxial plastic strains and stresses, was adopted in this analytical study. Yield stress σ_y = 294.7 [MPa], Elastic modulus E = 191.6 [GPa], Poisson's ratio ν = 0.276 were applied to all analytical models, respectively. The secondary seismic analysis for each seismic model (SM-1~SM-5) with different corrosion conditions, was performed by using the primary displacement histories obtained for each historical earthquake. The analyses were conducted until they reached their pre-defined termination limits and the load-displacement behaviour for each model was obtained.

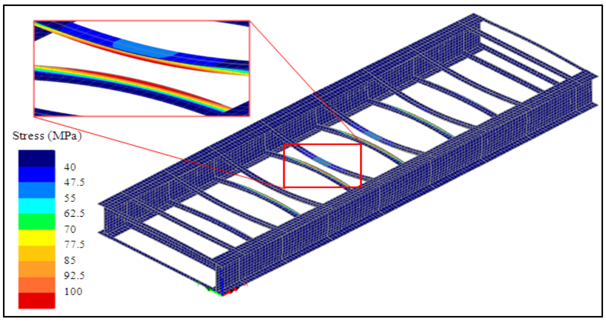
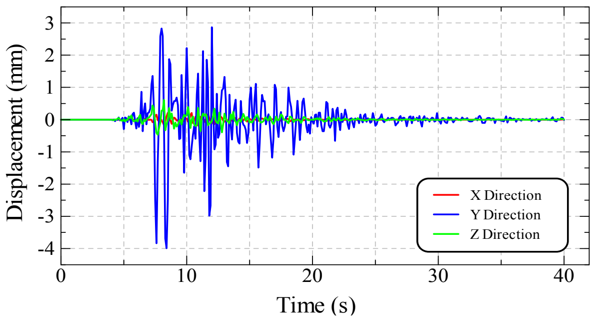


Fig. 6 Ultimate stress distribution of steel girder [1995 Kobe earthquake]



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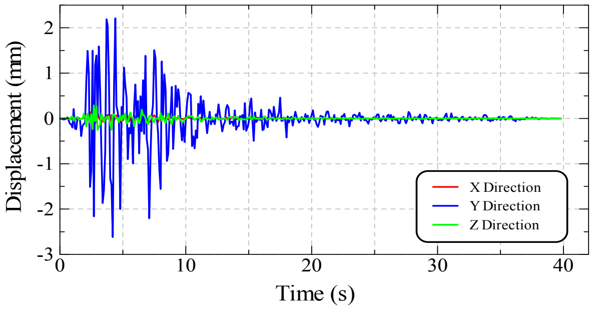

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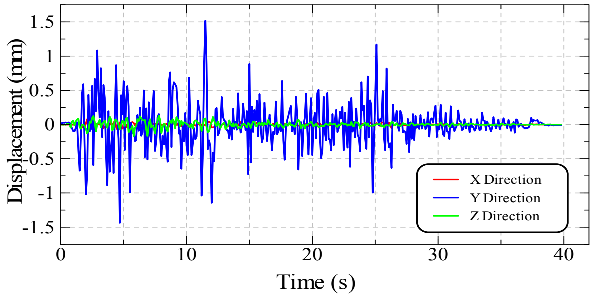


(c)

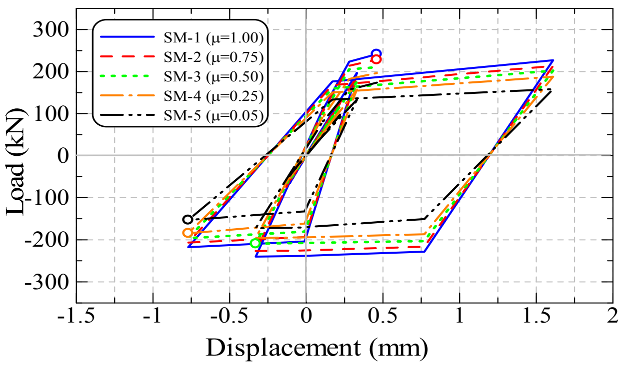
Fig. 7 Displacement histories of the critical member during (a) 1995 Kobe earthquake; (b) 1989 Loma Prieta earthquake and (c) 1940 El-Centro earthquake

TABLE II 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

D. Secondary Seismic Analysis Results and Discussion

Fig. 8 shows the load-displacement curves for (a) Kobe earthquake, (b) Loma Prieta earthquake and (c) El-Centro earthquake for each seismic model. They clearly show that the dynamic behaviour 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.



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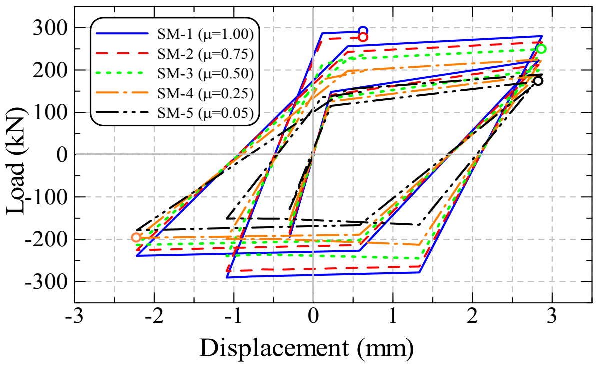

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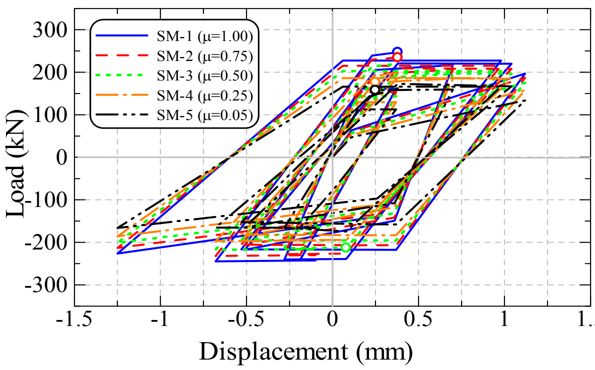

(c)

Fig. 8 Comparison of load-displacement curves of different seismic models for
(a) 1995 Kobe earthquake; (b) 1989 Loma Prieta earthquake and (c) 1940 El-Centro earthquake

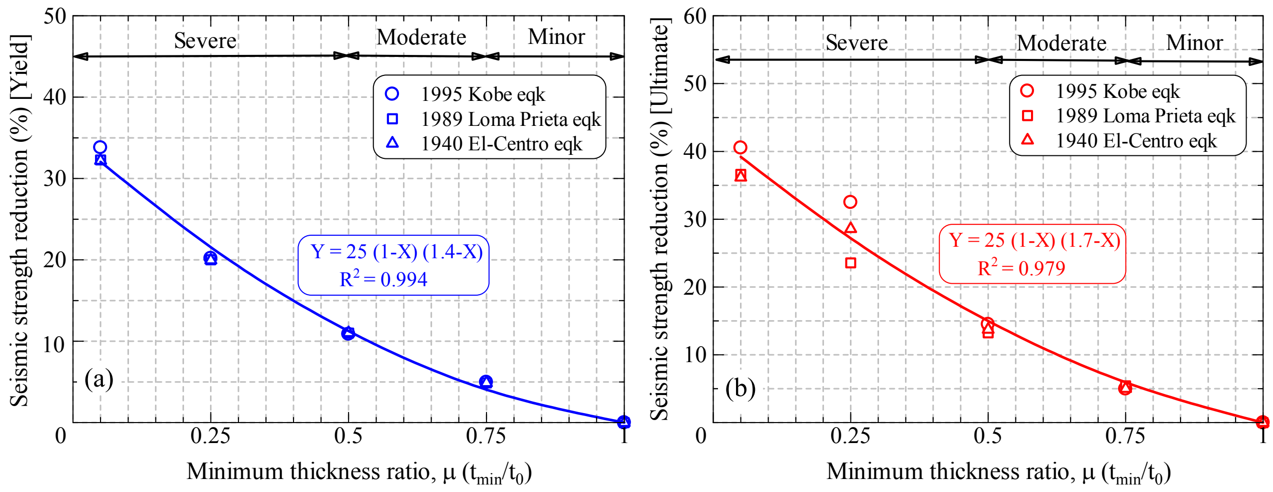

Fig. 9 Relationship of percentage (a) yield; (b) ultimate, seismic strength reduction vs. minimum thickness ratio (μ)

Figs. 9(a) and 9(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 the increase of corrosion levels. The remaining yield and ultimate seismic strength capacities are decreased with the severity of corrosion condition for all three 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. It is noted from Fig. 9 that two very good relationships can be obtained for remaining yield and ultimate seismic strength capacities with high accuracy. Therefore, by considering Figs. 9(a) and 9(b), two equations for estimating remaining yield and ultimate seismic strength capacities can be derived as:

$$\%SSR_{yield} = 25\ (1\text{-}\mu)\ (1.4\text{-}\mu) \tag{1}$$

$$\%SSR_{ultimate} = 25\ (1\text{-}\mu)\ (1.7\text{-}\mu) \tag{2}$$

As the proposed strength reduction equations only requires the measurement of minimum thickness ratio, μ (minimum thickness/ initial thickness), which is an easily measurable parameter through a quick and careful site investigation. This method can be used as a simple and reliable method to predict the seismic behaviours of corroded steel members more easily and precisely. Furthermore, as the %SSR chart gives a good indication about the percentage strength reduction according to the severity of corrosion, bridge engineers would be able to decide whether the infrastructure requires any initial corrosion prevention precautions such as painting etc., retrofitting of some selected members or replacement of some critical members in order to assure the adequate safety of the existing structure.

V. CONCLUSIONS

The yield, ultimate behaviours of steel members with different corrosion conditions were studied under different earthquake loadings. The main conclusions of this study can be summarized as:

1. Even though, the steel main girders behave well during severe earthquakes, some types of transverse members could become critical and hence could suffer various structural damages.

2. Corrosion and its stress concentration effect will trigger those damages significant and hence they could even lead to the collapse of total structure.

3. The percentage reduction of yield and ultimate strength capacities due to corrosion, under earthquake loadings can be defined as:

$$\%SSR_{yield} = 25\ (1\text{-}\mu)\ (1.4\text{-}\mu)$$
$$\%SSR_{ultimate} = 25\ (1\text{-}\mu)\ (1.7\text{-}\mu)$$

As the above remaining seismic strength capacity equations have only a single variable, minimum thickness ratio (μ), which is an easily measurable parameter, it will reduce the contribution of the errors occurred during the practical investigation of a corroded member. Furthermore, this method is simple and hence can be used for the maintenance management of steel bridge infrastructures with better accuracy.

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