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Experimental and numerical analysis of corroded steel plates subjected to compression buckling load

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ABSTRACT

The deterioration of materials in many old steel bridges due to environmental exposure becomes a serious problem in recent years not only in Japan but also all over the world. Therefore, the purpose of this research is to evaluate the residual strength capacity of corroded steel plates which are seen in steel structure under compression in order to keep them throughout in-service till necessary to rebuild or retrofit at appropriate time. The corroded plates with irregular surface were examined by experimental analysis which will help to decide the action plan in future. This paper presents the understanding behaviors of corroded plates where included parameters, i.e. representative average thickness with relation to compressive coefficient correction and amount of eccentricity, are considered conscientiously. Then, buckling test results of actual corroded plates reveal that surface configurations and amount of eccentricity decreased load-bearing capacity. Further, the numerical analysis has been conducted by the commercial finite element package Abaqus to understand the buckling behavior of corroded steel plates after validity of FEM model is confirmed.

1. INTRODUCTION

In Japan, many bridges were intensively constructed in the 1960s-80s. There are more than 50,000 steel railway bridges have been constructed, where a number of them have been used 50 years and exceeded the standard usage and service-life (Appuhamy 2012). Generally, main causes of deterioration in bridge structures are fatigue and environment. For steel bridges, one of the most dominant forms of the deterioration is corrosion that causes the loss of metal section resulting in a reduction of structural capacity and its performance (Kayser 1989). It has been pointed out that the corrosion can lead to rapture, yielding or buckling of steel members which can result in stress

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concentration and change in geometric parameters, then collapse will be occurred.

As a result, many bridges require substantial strengthening and repair works. For those bridges, detail and regular inspections are necessary in order to assure the adequate safety and satisfy the determined maintenance requirements in bridge infrastructure management. However, to develop a more reliable strength estimation technique for the actual corroded steel member, only experimental approach is not enough, but also the numerical approach could be considered to obtain a reliable estimation in bridge maintenance industry (Appuhamy 2011a). So far, number of researchers have continuously conducted some experimental and numerical studies to understand the behavior and calculate the residual strength of corroded steel plates under tensile load (Appuhamy (2011b), Appuhamy (2011c), Ohga (2011), and Ghavami (2006)).

Moreover, this study deals with the buckling behavior with both experimental and numerical analysis. Sugimoto (2006) carried out the loading tests and nonlinear FEM analysis with the corroded girder in order to reveal the relation between residual steel plate thickness and buckling strength for three buckling mood swings, the result revealed that local buckling occurs at minimum cross-sectional location.

Silva (2013) investigated numerically the effects of random localised corrosion thickness distribution on the ultimate strength of unstiffened rectangular steel plates in marine structure which subjected to uniaxial compressive load. It is shown that the finite element model has proven to produce good results and it is solely a great compromise between accuracy of corrosion discretisation, computational capabilities and time.

Kim (2013) made a study about shear loading tests on plate girder specimens in order to evaluate shear behaviors of locally corroded web panels, including their critical shear buckling loads and shear strengths. In that study, the shear loading tests were conducted on steel plate girders with corroded webs, which were fabricated by the mechanical process.

Khedmati (2010) analyzed the mechanical behavior of plates which suffered from general corrosion on their both surfaces and subjected to uniaxial in-plane compression numerically.

From studies mentioned above, until now there is still less of knowledge to assess the behavior of corroded steel bridge plates under compression load. To investigate and understand its behavior, the experimental analysis was carried out in this study. Before carrying it out, by using a two-dimensional laser displacement sensor we measured the irregularity of steel plate throughout its both surfaces. Further, FEM was conducted by using the commercial finite element analysis Abaqus/standard to confirm the validity of experimental results. Thus, it is exigent task to identify and assure the adequate safety and maintenance requirements in bridge infrastructure management whether those bridges are necessary to rebuild, retrofit or other proposed method. Therefore, the main purpose of this research is to evaluate the residual strength capacity of corroded steel plates which are seen in steel structure under compression in order to keep them throughout in-service till necessary to rebuild or retrofit at appropriate time.

2. EXPERIMENTAL INVESTIGATION

2.1 Test Specimen Configuration

The compression test specimens were cut out from flange of the steel girder at

Amarube Bridge located in Hyogo Prefecture which had been used for 98 years. In this research, 9 test specimens (FM1-FM9) were fabricated for the use of compression test. Before conducting the thickness measurement, all rust and painting throughout both surfaces were removed carefully by using electric wire brush and punches. Then, two of new SM490A steel material with a hole bolt were jointed and welded at each both end sides of test specimen for gripping parts of loading compression machine as shown in Fig. 1. In addition, 3 regular specimens (JIS No.5 type) seen in Fig. 2 were tested in order to clarify the properties of material specimen as shown in Table 1.

Here, the test specimens have range from 75mm - 88mm in widths respectively. After all, the irregular surfaces of the corroded specimens were measured by using a two-dimensional laser displacement sensor and buckling tests were conducted by testing machine of which maximum load capacity is 120kN. Then, the loading velocity adjustment was arranged where for a specimen test with light corrosion was 0.15kN/sec and about 0.05kN/sec for severe corrosion in order to avoid the dynamic failure.

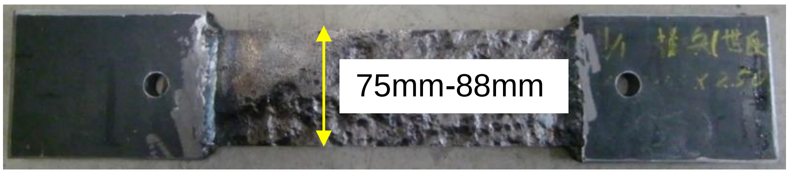


Fig. 1 Test specimen of corroded steel plate.

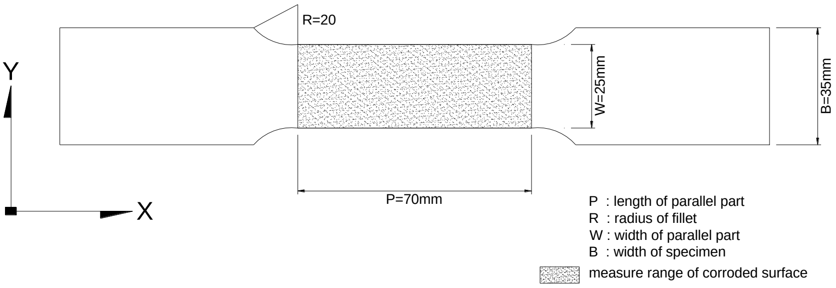


Fig.2 JIS No.5 Specimen for buckling test

2.2 Thickness measurement of corroded steel plate

Accuracy, convenience, portability and lightness are highlight demanded to choose a device for the on-site measurement of corroded surface irregularities. Therefore, the gauging system with two-dimensional laser displacement sensor was adopted to the surface shape measurement of this test specimens at which combined with the sensor head and an electric actuator devices. Solely, the surfaces of all the corroded specimen were measured in x directions with adjusting pitch measurement of 2.0mm at both sides and y direction was taken as a basic level of measurement point as shown in Fig. 3(a).

For measuring the corroded thickness plates (z direction), we obtained the data by using plate thickness method that seen in Eq. (1) as follows:

$$t_1 = \Delta h_1' + t_a - \Delta h_1 \tag{1}$$

where $\Delta h_1'$ and Δh_1 are the distance between any point and reference plate respectively and t_a is determined. Table 2 summarizes the measurement result of average thickness plate t_{avg}, minimum thickness plate t_{min}, maximum thickness plate t_{max} and central average thickness plate that was obtained from actual corroded plates girder respectively as seen in Fig. 3(b).

Table 1 Material properties.

Specimen	Elastic modulud/(Gpa)	Poisson's ratio	Yield stress/(Mpa)	Tensile strength/(Mpa)	Elongation after breaking
FM-1	203.3	0.287	257.85	383.36	41.4
FM-2	199.3	0.283	281.06	386.4	38.52
FM-3	200.3	0.282	269.09	390.59	39.23
SS400 JIS	200	0.3	245”	400”510	21”

Table 2 Measurement of plate thickness results

Specimen	Average thickness plate t_{avg} (mm)	Minimum thickness plates t_{min} (mm)	Maximum thickness plate t_{max} (mm)	Minimum average thickness plate (mm)	Central average thickness plate (mm)
AF-1	14.788	11.175	15.9	13.697	15.4
AF-2	11.084	7.426	15.217	9.603	11.544
AF-3	10.164	5.242	14.407	9.122	10.171
AF-4	13.732	8.626	15.9	12.552	13.028
AF-5	14.544	9.347	15.9	13.047	14.711
AF-6	14.61	10.707	15.9	13.629	14.512
AF-7	13.994	10.078	15.9	11.147	14.209
AF-8	12.737	8.465	15.9	10.704	13.678
AF-9	15.399	11.127	15.9	14.617	15.542

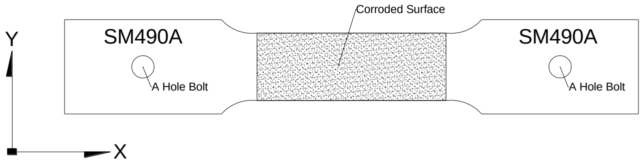


Fig. 3(a) Coordinate system of specimen test

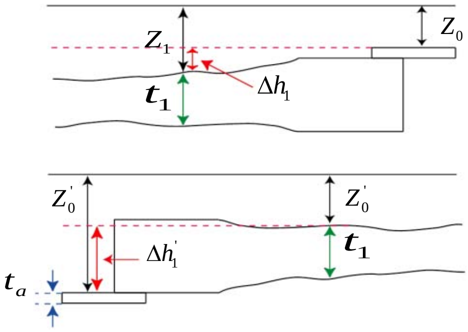


Fig. 3(b) Plate thickness calculation

2.3 Experimental Result

Generally, Euler buckling load in Eq. (2), for calculating the buckling strength with non-corroded condition where P_{cr} is maximum vertical load, E is modulus of elasticity, I is area moment of inertia, k is effective length factor which depends on the condition of end support specimen test, and L is unsupported length of specimen test, is used as a simple analytical method. However, since the Euler buckling load formula is not appropriate for the buckling phenomenon and behavior of corroded steel specimen, it is just used as a basic reference calculation to obtain the residual compression strength that subjected to corroded steel plate which is presented in this study.

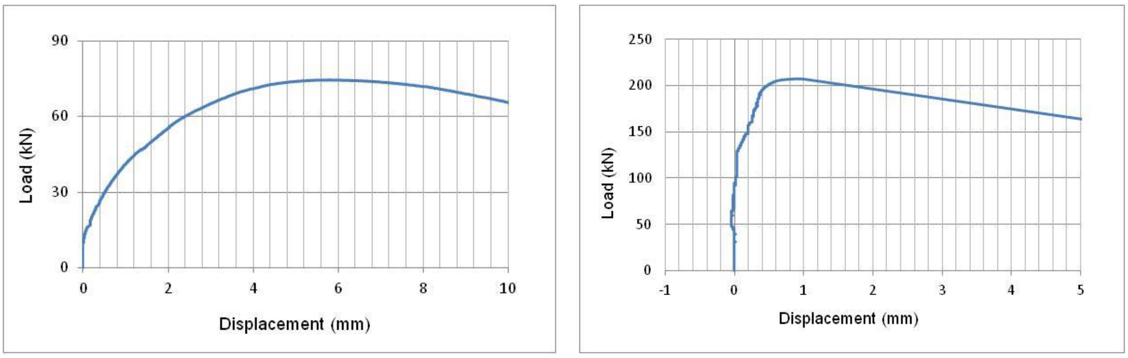
$$P_{cr} = \frac{k\pi^2 EI}{L^2} \tag{2}$$

In Table 3 is shown the results of buckling strength, Euler buckling load, effective buckling length and buckling type where to assess the effective buckling length is depend on the end of specimen support. It also reveals that the experimental analysis has average lower strength than Euler buckling load. it is believed that loss of cross-sectional specimen and localization due to corrosion influences the buckling strength.

In this study, prefer model to be investigated are AF-4 and AF-9 where load-displacement results are shown in Fig. 4(a) and 4(b) respectively. Both figures show the influence of eccentricity which AF-4 is greater than AF-9 because it has distinct minimum thickness plate which is calculated around 15%. Furthermore, the investigations of load-strain relation among specimens of AF-4 and AF-9 are shown in Fig. 5(a) and 5(b) respectively. From those figures it has revealed that the stress throughout AF-4 specimen concentrates on the minimum thickness part and local buckling behavior was occurred. Moreover, on the contrary, for AF-9 has shown total buckling behavior which was occurred throughout the specimen. Therefore, the compression of buckling behavior, whether that is either local or total buckling, is occurred due to subjected to corrosion and amount of eccentric of steel plate. Then, Fig. 6 shows the corroded specimen set up to obtain the residual strength by experimental analysis.

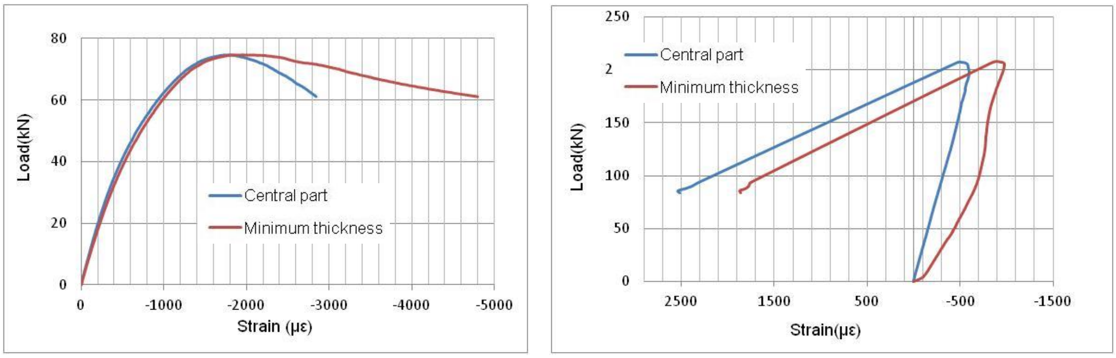
Table 3 Buckling load, Euler buckling load, Effective buckling length and Buckling type

Specimen	Buckling Load (kN)	Euler buckling load (kN)	Width	Effective buckling length (mm)	Buckling type
AF-1	81.6	129.7	78.0	636	Total buckkling
AF-2	43.3	149.7	87.8	628	Total buckkling
AF-3	41.3	121.6	74.9	646	Total buckkling
AF-4	74.6	132.7	81.9	644	Local buckkling
AF-5	60.6	117	85.8	702	Total buckkling
AF-6	92.8	140	88.0	650	Total buckkling
AF-7	60.7	141.2	85.5	650	Total buckkling
AF-8	79.7	132.7	81.9	638	Total buckkling
AF-9	207.1	138.4	83.8	644	Total buckkling



(a) AF-4 (b) AF-9

Fig.4 Comparison of load-displacement curve of (a) corroded steel member AF-4 and (b) corroded steel member AF-9



(a) AF-4 (b) AF-9

Fig. 5 Load-strain relation (a) local buckling (b) total buckling

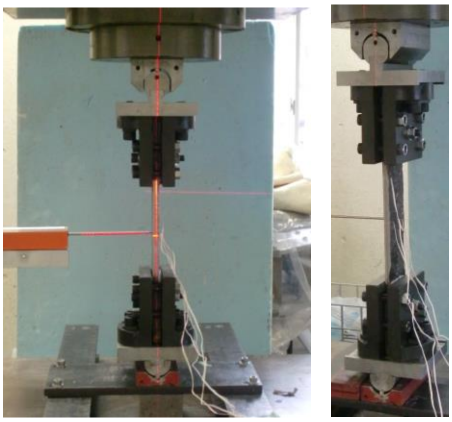


Fig. 6 corroded specimen set up

3. NUMERICAL INVESTIGATION

3.1 Analytical Model

The nonlinear finite element analysis was performed to the specimens with their actual conditions. The continuum three-dimensional solid element with hexahedral nodal points (C3D8R) and updated Riks method based on incremental theory as an analytical control were adopted in this analyses. Then nonlinear elastic-plastic material and Von Mises yield criterion ware assumed for material properties. The analytical model (AF-1) with length (X), width (Y), and depth (Z) dimensions were modeled with their respective corrosion condition as seen in Fig. 7.

In addition, 2.0mm regular mesh pattern was adopted to all analytical model and it was assumed that the boundary condition at both ends was pinned support which would be able to rotate freely and it was equally assumed as actual experimental condition.

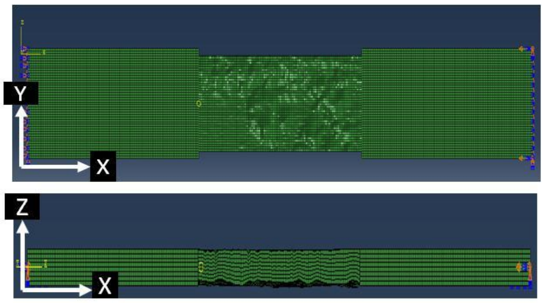


Fig. 7 Analytical model of AF-1 that similar to actual condition

3.2 Analytical Result

Fig. 8 shows the comparison of remaining strength capacity of corroded steel plates which subjected to buckling load to all specimens in experimental and analytical analyses. Here, having a coefficient of correlation of $R^2 = 0.99$ indicates the accuracy of the proposed model and the possibility of the use of proposed analytical model instead of the model with detailed corroded surface measurement. Therefore, it is evident that the use of proposed analytical model by commercial finite element analysis Abaqus/standard can estimate the residual strength capacities of corroded steel plate members more easily and accurately

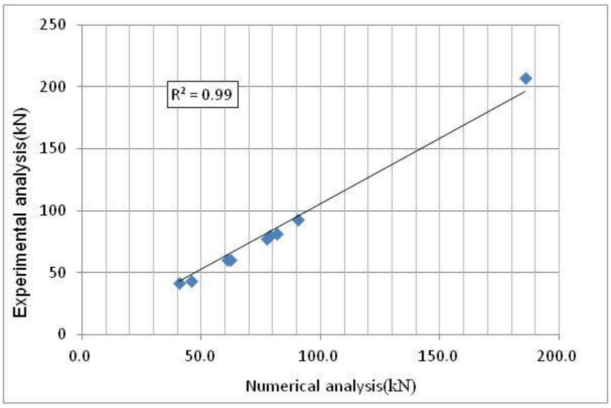


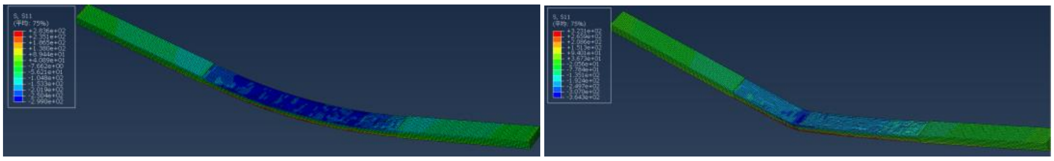
Fig. 8 Comparison of remaining strength in experimental and numerical analysis

4. PARAMETRIC STUDIES

4.1 Corroded Steel Plate

The remaining strength behavior of dimensional changes of corroded strip plate under compression load is considered here. In addition, 8 specimen models that conducted and investigated by finite element method as parametric study is also studied here where those were cut out from the horizontal flange strip of Ferry Contact bridge subjected to environmental exposure in seawater condition that was already studied by us previously and those were also known that have equal dimensions and feature conditions. Furthermore, the measurement of plate thickness and remaining buckling strength results can be seen in Table 4 respectively.

From the Table 4, it is understood that the residual compressive strength tends to grow up when the effective buckling length is becoming shorten due to the surface loss and the irregularity of surface specimen. Moreover, as result of the irregularity of surface specimen can generate total and local buckling behaviors as shown in Fig. 9(a) and 9(b).



(a) (b)

Fig. 9 Compressive strength (a) total (b) local buckling

Table 4 Measurement and experimental results

Specimen	Effective buckling length (mm)	Average plate thickness (mm)	Minimum plate thickness (mm)	Minimum average plate thickness (mm)	Central average thickness plate (mm)	Remaining buckling strength (kN)
CF4501	840	9.237	6.86	8.313	9.34	5.98
CF4502	840	8.333	6.03	7.219	7.255	4.28
CF3001	690	9.301	6.51	8.527	9.345	10.07
CF3002	690	8.463	6.27	7.58	8.226	7.77
CF3003	690	8.727	7.29	8.041	8.916	8.4
CF3004	690	9.086	7.71	8.639	8.888	9.47
CF1501	540	9.623	6.81	9.017	9.81	24.39
CF1502	540	8.181	5.63	7.07	8.409	14.91

4.2 Amount of Eccentric Change

Herein, the parametric study of 110 patterns was studied and the changes of residual compressive strength plates with their amount of eccentric and irregular corrosion were also verified briefly. Furthermore, From Fig. 10 is understood that when the residual compressive strength decreases, the eccentricity will increase linearly. Therefore, likewise the ultimate strength, the buckling strength solely depends on the width, thickness, and length of corroded specimen.

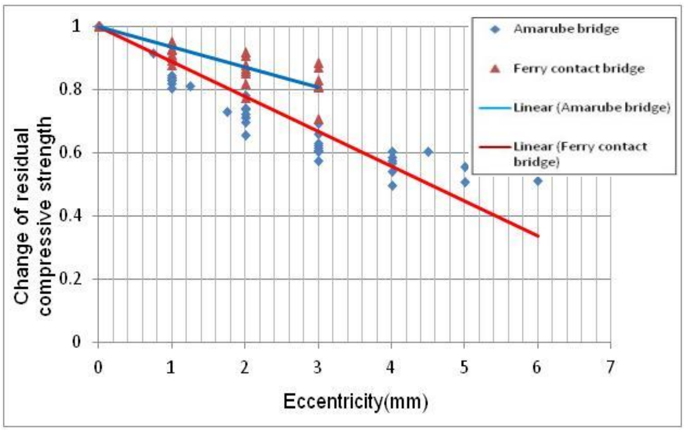


Fig. 10 Change of residual compressive strength-eccentricity relation

5. PROPOSE RESIDUAL BUCKLING STRENGTH FORMULA

The proposed residual buckling strength of corroded steel plate formula with irregular surface is mainly discussed in this present study. As obtained results in previous discussion by experimental and numerical methods reveal that some factors which influence the residual compressive strength such as surface shape, corrosion level, effective buckling length and amount of eccentric specimen are considered carefully.

Euler buckling load is generally expressed by using Eq. (2). In this study, because the end condition was pinned support, the buckling strength of corroded plate will become Eq. (3) as follows:

$$P_{cr} = \frac{\pi^2 EI}{L^2} \tag{3}$$

Where,

$$I = \frac{bt_{eff}^3}{12} \tag{4}$$

Then, by substituting Eq. (4) to Eq. (3), P_{cr} becomes as follows:

$$P_{cr} = \frac{\pi^2 EBt_{eff}^3}{12L^2} \tag{5}$$

From Eq. (5), it is obvious that the influences of width *B* and the effective buckling length *L* decide the result of buckling strength. Moreover, the effective thickness plate t_{eff} in residual compressive strength of corroded steel plate, that based on the initial thickness t_0 and minimum thickness t_{min}, is considered in this study. Herein, it is assumed that equal to the average thickness t_{avg}.

As seen in Fig. 11 that satisfied correlation between unit load P which neglect to the influence of its parameters and effective thickness t_{eff}^3 without eccentric behavior which expressed in Eq. (6) as follows:

$$P = \frac{12P_{cr}L^2}{\pi^2 EB} \tag{6}$$

Furthermore, the influence of amount of eccentric behavior of corroded steel plate is studied briefly here. Fig. 12 shows high correlation between the compressive coefficient correction β and eccentric ratio α, it can be expressed in Eq. (7) as follows:

$$\beta = -0.39\alpha + 1 \tag{7}$$

Where α is in Eq. (8) as follows:

$$\alpha = \frac{eBt_{avg}}{t_0^3} \tag{8}$$

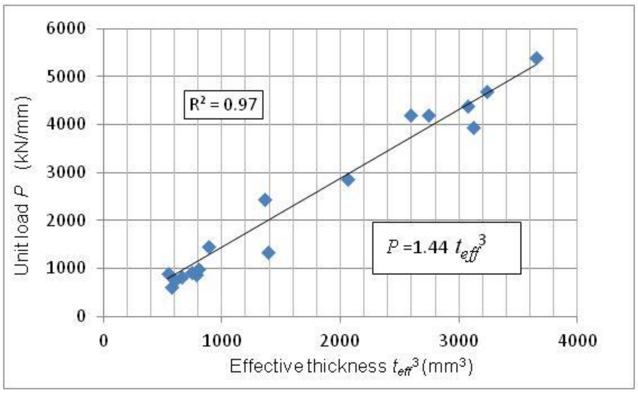


Fig. 11 Relationship of unit load - effective thickness

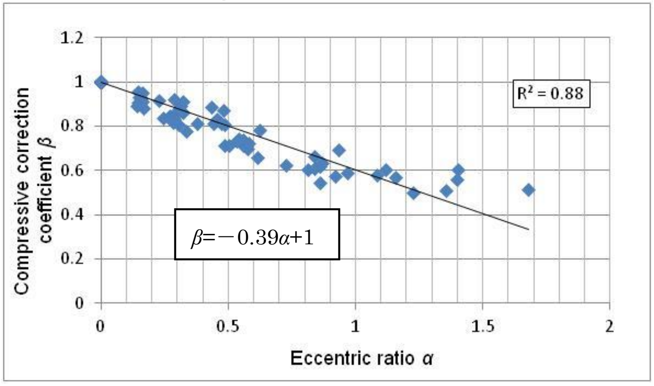


Fig. 12 Relationship of compressive correction coefficient - eccentricity

Therefore, from previous explanation, a new formula can be obtained for calculating the residual compressive strength of corroded steel plate by considering the influence of effective thickness and amount of eccentric behavior that can be seen and expressed in Eq. (9) as follows:

$$P_{cr} = \frac{0.12\pi^2 \beta E B t_{eff}^3}{L^2} \tag{9}$$

6. CONCLUSIONS

The buckling tests were performed by experimental and numerical analysis to clarify the residual strength of corroded steel plates in the present study. Compression buckling load of corroded steel plate test results showed that local and total buckling behavior were occur at the specimen tests. Therefore, from this study shows that the behavior of amount of eccentricity and corroded steel plate are influenced and reduced the residual strength that subjected to buckling load. Then, propose formula to calculate the residual strength due to some behavior of average thickness, however in this study, assumed that average thickness is equal to effective thickness, which correlated to compression coefficient correction and eccentric ratio that shown as follows:

$$P_{cr} = \frac{0.12\pi^2 \beta E B t_{eff}^3}{L^2}$$

This study solely shows that non-linear FEM analytical results indicated a very good comparison of the experimental and analytical buckling strength. Therefore, it can be conclude that the adopted numerical modeling technique can be used to predict the residual strength capacities of actual corroded members accurately.

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