Calibration of the Fiber Model for Seismic Design of Elevated Highway Steel Piers

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The ratio of the allowable strain to yield strain and the ratio of allowable curvature to yield curvature are considered as parameters for expressing the seismic performance criterion of the allowable displacement of steel bridge piers. Also an investigation is conducted into the influence of cyclic loading pattern and axial load on strain and curvature results. The results show that curvature is preferred over strain as it is not affected by loading pattern and or applied axial load. This result is confirmed by plotting the calculated values of a pier's allowable displacement and maximum load via strain and curvature results. Furthermore, a comparison of the analytical results to experimental values shows the validity of the fiber model for use in steel pier design.

Key words: fiber model, allowable displacement, strain, curvature

1. Introduction

1.1 General

The steel piers of elevated highway bridges in Japan suffered heavy damage during the Hyogo-ken Nanbu Earthquake in January 1995[1]. The tragedy resulted in many research studies that were directed at improving the knowledge of seismic performance of steel piers. The consequent 1996 revised seismic design specification stipulated that piers should be designed according to the ductility design method and seismic performance be estimated by a nonlinear dynamic analysis[2]. The analysis is used to verify that the displacement response lies within the allowable displacement range of the pier. Such an analysis requires the setting of a hysteretic restoring force model for which there are currently; (1) the horizontal load to displacement (P-δ) model; (2) the moment to curvature (M-ϕ) model and; (3) the stress-strain (σ–ε) model, also known as the fiber model[3].

1.2 Restoring Force Models

The first model, the P-δ model, is simpliest of the three and is only applicable to simple piers as it has difficulty in handling complex piers, rigid frames as well as arch structures. The second model, the M-ϕ model, is more complex and can be applied to simple piers and rigid frames and for this reason is adopted, along with the P-δ model, for actual design[4]. Nevertheless, in the event of the large axial force changes or bi-axial bending, the validity of the M-ϕ model is uncertain and subsequent thorough verification is required. The last model, the fiber model, uses a hysteretic restoring force model calculated directly from the stress-strain relationship. It is able to handle large axial force changes and bi-axial bending naturally and therefore, in comparison with the other models, has the highest application[5]. However, currently there are few studies to show the application of the fiber model for use in the actual seismic design of steel bridge piers[6-9]. Consequently, this research sets out to conduct a fundamental investigation into the setting of the fiber model for the

estimation of allowable displacement of non-concrete filled rectangular section steel bridge piers with the use of cyclic experimental data.

2. Cyclic Loading Experiments

Following the Hyogo-ken Nanbu earthquake, extensive cyclic loading testing on approximately 1/3-scale specimens was conducted to increase the understanding of steel bridge pier failure mechanisms under earthquake type loading[10]. The experiments were conducted with a constant axial force applied by a jack and horizontal load applied by an actuator as shown in the experiment setup in Figure 1. Using a cyclic loading pattern to simulate the response of an earthquake, the results of the experimental loading for one of the rectangular section specimens, KD-6, are as are shown in Figure 2.

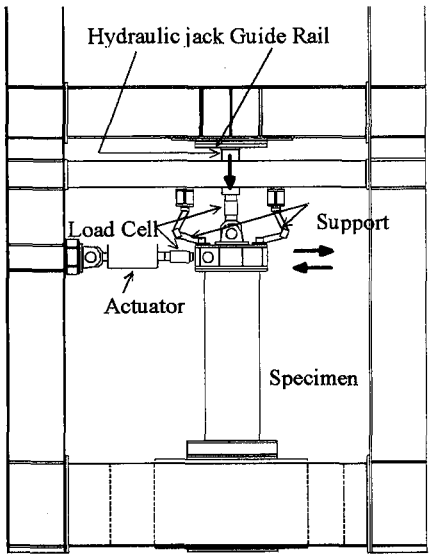

Fig.1 Experimental setup

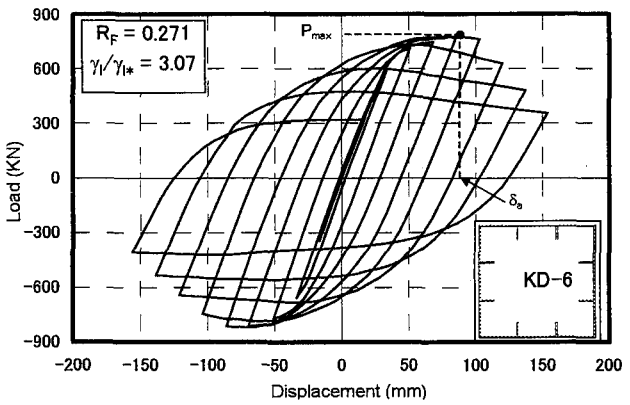

Fig.2 Experiment result for specimen KD-6

3. Setting the Restoring Force Fiber Model

According to the revised seismic design specification, seismic performance of steel piers must be validated by ensuring that under a non-linear dynamic analysis the maximum response displacement is within the allowable displacement. The allowable displacement is one way of representing the limit condition of steel pier however it is important that through a non-linear dynamic analysis the allowable displacement can be achieved with good accuracy. There are a few proposals for setting the allowable displacement[11]. However, this research uses the above-mentioned cyclic experiments for which the allowable displacement (δ_a) is defined as the displacement at which maximum load occurs as depicted in Figure 3. As a result, an investigation into the setting of the fiber model for the accuracy in estimating the allowable displacement of steel bridge piers is conducted. Figure 4 shows the bilinear model that is used as the stress-strain model in the fiber model. The kinematic hardening rule applies for the case of a cyclic analysis.

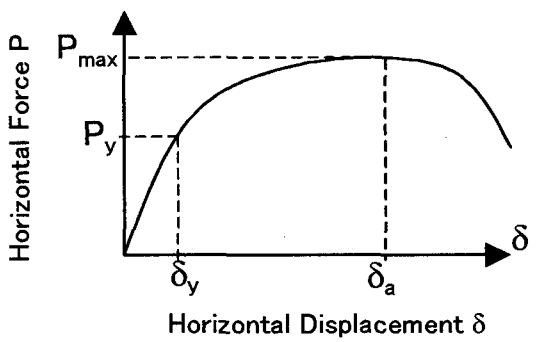

Fig.3 P-δ relationship

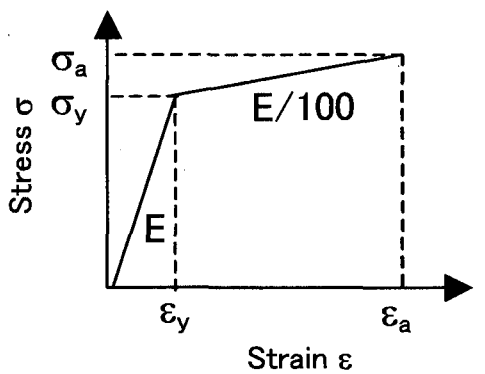

Fig.4 Bilinear σ–ε model

4. Strain and Curvature

In the analysis, 17 experimentally tested rectangular section specimens are loaded until the allowable displacement (δ_a) is reached through either a pushover or cyclic analysis. Pushover, as the name suggests, loads the specimen uniformly until the allowable displacement is reached. For a cyclc loading pattern, the specimen is subjected to oscilating displacement to which incremental values of yield displacement are added until the allowable displacment is reached. These patterns are as shown in Figure 5.

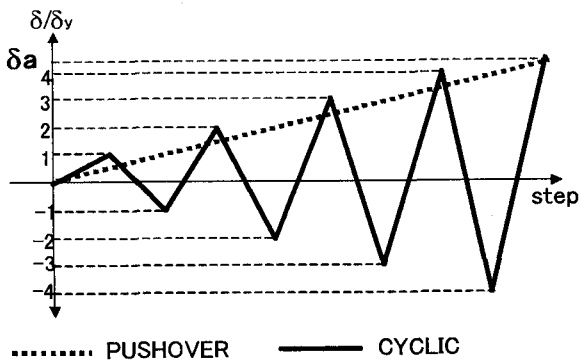

Fig.5 Pushover loading and cyclic loading pattern

This analysis proposes both strain and curvature as parameters for evaluating the seismic performance under a non-linear dynamic analysis. These results are normalized by formulating the ratio of allowable strain to yield strain ($\varepsilon_a/\varepsilon_y$) and the ratio of allowable curvature to yield curvature (ϕ_a/ϕ_y). Curvature is not obtained directly from the analysis and so must be calculated by taking the difference between compression and tension face strains and dividing by the cross section width. The allowable strain and curvature are then defined as that of corresponding to the base compression face of the pier upon being subjected to allowable displacement determined by a cyclic loading experiment.

For both pushover and cyclic analysis, the results of strain and curvature were graphed against a various array of pier parameters, such as the width-to-flange thickness ratio R_F, width-to-stiffener thickness ratio R_R, slenderness ratio $\overline{\lambda}$ and axial force ratio N/N_y as shown in Equations 1 to 4.

$$R_F = \frac{b}{t}\sqrt{\frac{\sigma_{yM}}{E}\frac{12(1-\mu^2)}{\pi^2 k_F}} \qquad (1)$$

$$R_R = \frac{b}{t}\sqrt{\frac{\sigma_{yM}}{E}\frac{12(1-\upsilon^2)}{\pi^2 k_R^{\,2}}} \qquad (2)$$

$$\overline{\lambda} = \frac{1}{\pi}\sqrt{\frac{\sigma_{yM}}{E}}\frac{l}{r} \qquad (3)$$

$$\frac{N}{N_y} = \frac{N}{A\,\sigma_{yN}} \qquad (4)$$

Where;

b = flange width,
t = flange plate thickness,
σ_{yM} = material lower yield stress,
E = Young's modulus,
υ = Poisson's ratio (=0.3),
k_R = buckling coefficient of plate,
k_F = buckling coefficient of stiffened plate,
r = radius of gyration,
A = cross section area and,
σ_{yN} = nominal yield stress.

Amongst the correlations, the highest correlation was achieved with R_F. Further investigation into combinations of parameters revealed a slightly better correlation from multi-parameter $R_R x R_F(1-N/N_y)$ yet the extent to which this parameter understandable is a judgement decision. The authors believe that the sheer simplicity of single parameter R_F out weighs the increase in correlation. Thus unanimously R_F is used to correlate against strain and curvature results. Figure 6 shows the results of strain plotted against parameter R_F.

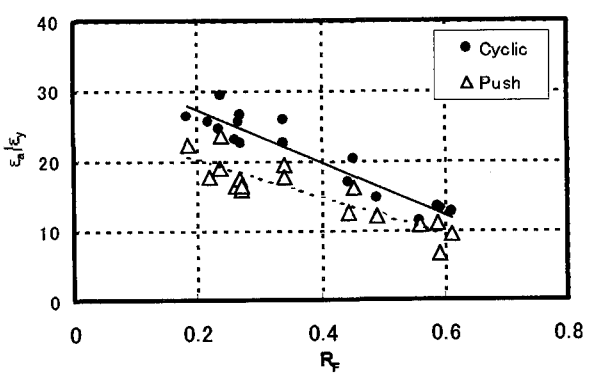

Fig.6 Strain ratio results

In the results, a strong negative correlation was found for both pushover and cyclic results and consequently a linear regression line was plotted. The negative correlation indicates that specimens with high R_F values underwent lower strain than low R_F specimens at maximum load. Furthermore, it is possible to ascertain that a pushover analysis produces lower strain results than that of a cyclic analysis. This is indicative of the influence of the axial force present which for increasing cycles causes the strain to accumulate thus shifting towards the compression side. This increase due to cyclic loading is confirmed in the stress-strain hysteresis loop of KD-6 as in Figure 7.

The results of allowable curvature to yield curvature (ϕ_a/ϕ_y) graphed against R_F are shown in Figure 8. Similarly, a strong negative correlation was found. However unlike strain results, the curvature results of pushover and cyclic analyses are practically identical. This indicates that an increase in cycles has no influence on curvature whereas strain is influenced considerably[6,7].

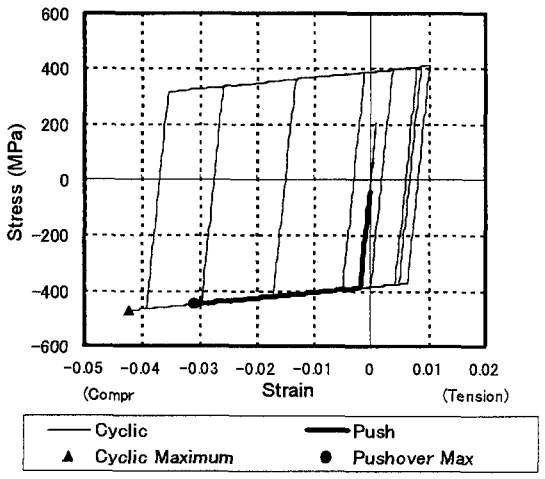

Fig.7 Stress-strain hysterisis loop for KD-6

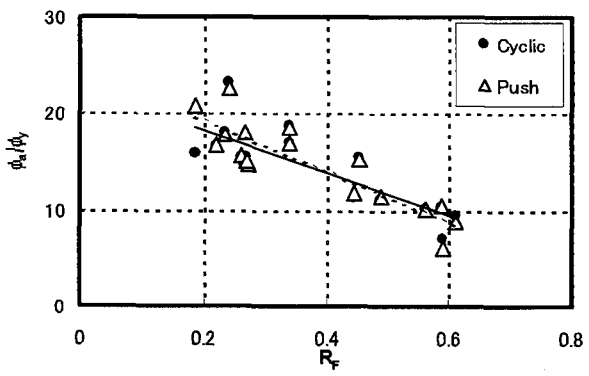

Fig.8 Curvature ratio results

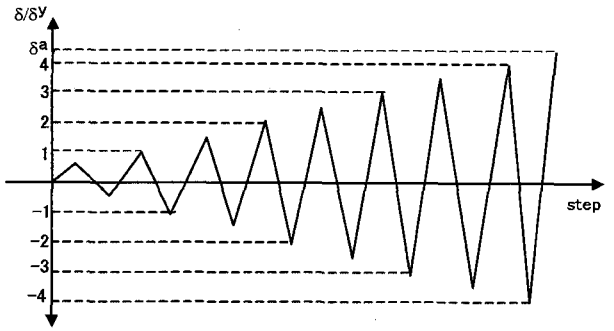

Fig.9(a) Double step cyclic loading pattern

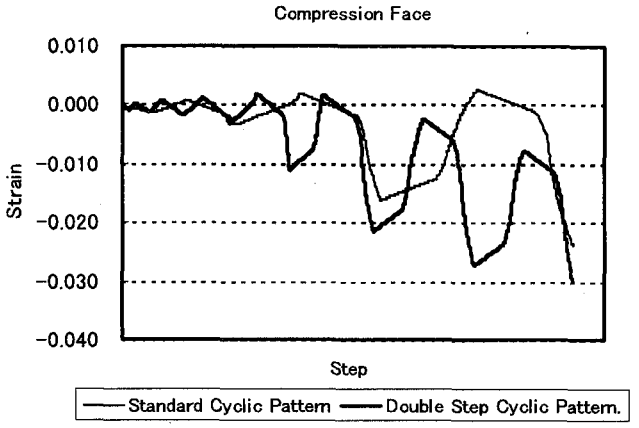

Fig.9(b) Compression face strain

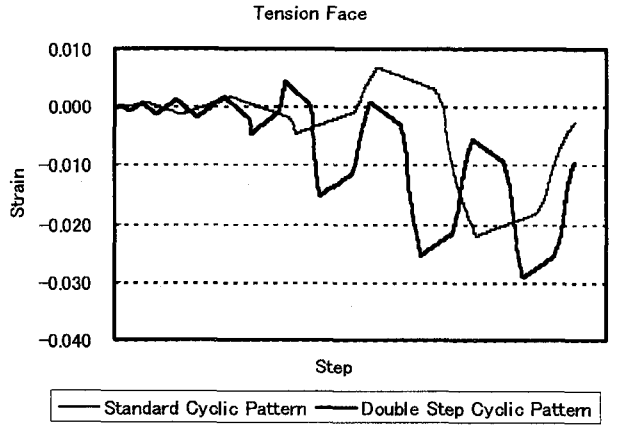

Fig.9(c) Tension face strain

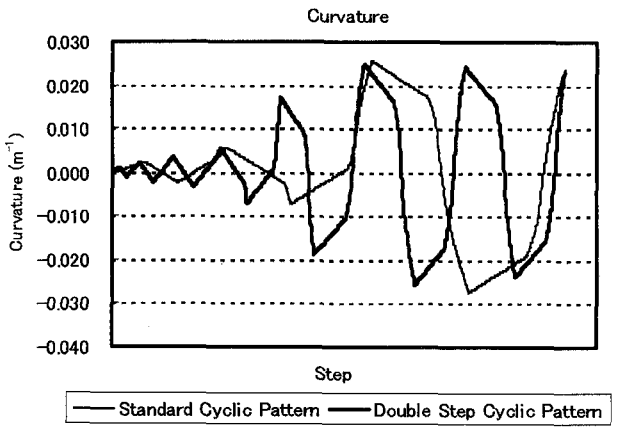

Fig.9(d) Base curvature

5. Cycle Influence Study

During an earthquake the loading pattern may take any form. As a result, an investigation into the influence that the cyclic loading pattern exhibits on strain and curvature results was conducted. The standard cyclic pattern was doubled to include two cycles per increment in yield displacement as shown in Figure 9(a). The result was to increase strain on the compression face as exemplified by specimen No.18 in Figure 9(b). This is justifiable as from increasing the number of cycles the effect of the applied axial load would have a more prominent effect on the induced strain in the compression face of the steel pier.

As for curvature, since the tension face resulted in an equal and opposite reduction in allowable strain (Fig. 9(c)), there was no change in the allowable strain difference. As a result there was no change in result for allowable curvature as shown in Figure 9(d). From this investigation it is concluded that allowable curvature to yield curvature ratio (ϕ_a/ϕ_y) is independent of the cyclic loading pattern, where as increasing the cycles causes the allowable strain to yield strain ratio ($\varepsilon_a/\varepsilon_y$) to increase.

6. Axial Force Ratio Study

To investigate the influence of axial force ratio on strain and curvature, the axial force was omitted and the analysis conducted for both pushover and cyclic loading patterns. The result was to cause strain to decrease as shown in Figure 10(a) for a cyclic pattern. However, analagous to the cycle influence investigation, the tension face strain moved equally and oppositely resulting in an increase in strain. Thus the resulting strain difference between compression and tension faces remaining unchanged (Fig. 10(b)). Similarily, there was no change to the curvature of the pier (Fig. 10(c)). This counterbalance effect shows that in the results of curvature, omitting the axial force yields no effect on the allowable curvature of the pier. Furthermore, omitting the axial force causes strain results of pushover and cyclic anaylses to converge together as shown in Figure 10(d). With no axial force, the strain values do not diverge but oscilate symmetrically to the horizontal axis. This indicates that in the specific case of no axial force, strain is independent of cyclic pattern[6,7]

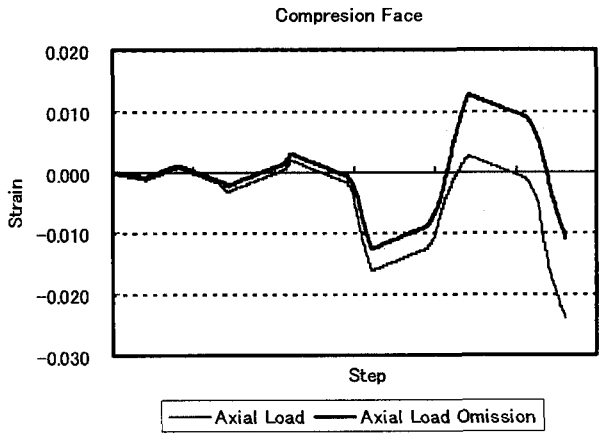

Fig.10(a) Compression face strain

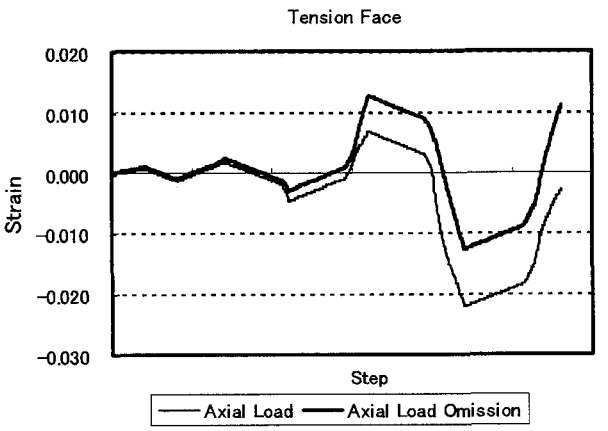

Fig.10(b) Tension face strain

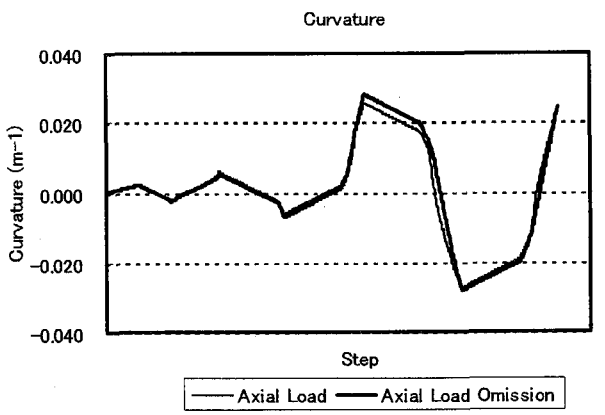

Fig.10(c) Base curvature

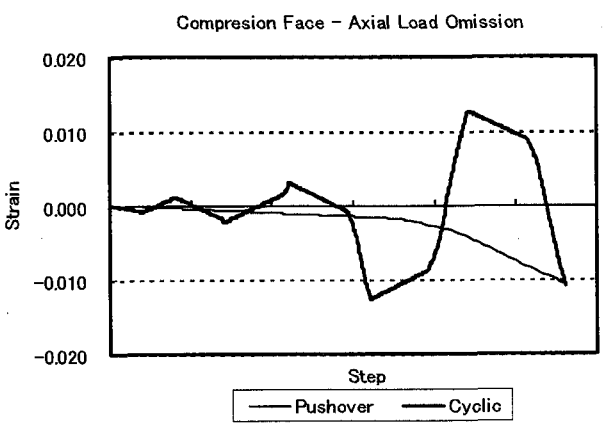

Fig.10(d) Comparison of pushover to cyclic strain

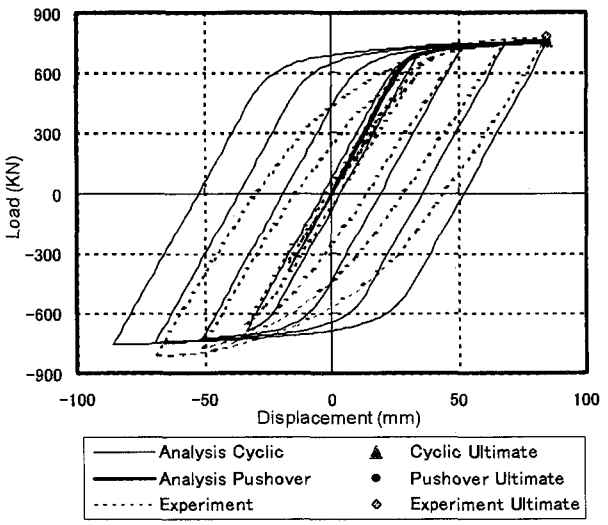

Fig.11 P-δ relationship of pushover analysis, cyclic analysis and experiment result for KD-6

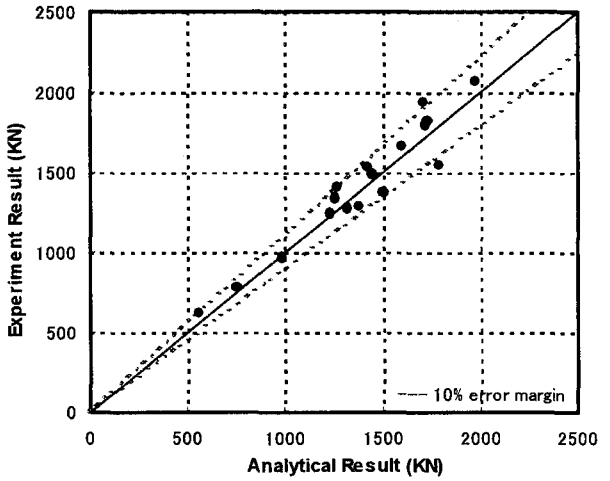

Fig.12 Comparison of Maximum Load (P_{max}) for analysis and experiment

7. Comparison with Experimental Results

The P-δ relationship is the curve formed by plotting horizontal load versus horizontal displacement of the tip of the pier. The maximum point defines the maximum horizontal load (P_{max}) and the allowable displacement (δ_a) as shown previously in Figure 2.

Pushover and cyclic analysis results of P-δ relationship were compared with that of gained by the experimental cyclic loading test conducted by the Public Work Research Institute (PWRI)[10]. As an example of the comparison of experiment and analysis results, Figure 11 shows the results for case of specimen KD-6.

At first glance, one notes that the hysterisis curves for cyclic loading do not match. This is a as a result of the bilinear model used. However, the primary concern is that of the maximum horizontal load for which comparison with experiment results shows good accuracy for both pushover and cyclic analysis.

Thus, in comparing the maximum load of the experiment to analysis for all specimens, Figure 12 shows the result of lie within a mere +/-10% error margin line. Since the maximum horizontal load is not the target of the analysis, rather that of allowable displacement, this degree of error is considered acceptable.

8. Calculation of Allowable Displacement and Maximum Load

An investigation was done into the ability to calculate the allowable displacement and maximum load of the experiment by using the correlation and regression results obtained by the result of the 17 previously analysed piers. The calculation was done for both that of strain and curvature based results.

8.1 Calculation by Strain Results

For strain results, the procedure is as follows. First the specimen parameters' R_F and yield strain are attained. Next, linear regression lines for both pushover and cyclic analyses are determined from the correlation between allowable to yield strain ratio and parameter R_F for all specimens. Using these regression lines plus the specimens' R_F and ε_y, a value of allowable strain can be obtained. This value, named the calculated value of allowable strain, is then used and compared to a pushover analysis and a corresponding value for allowable displacement and maximum load are obtained. The calculated value of allowable displacement and maximum load can then be compared to the experiment values and the accuracy of the method for strain results be evaluated. This procedure is pictorially represented in the flowchart depicted by Figure 13.

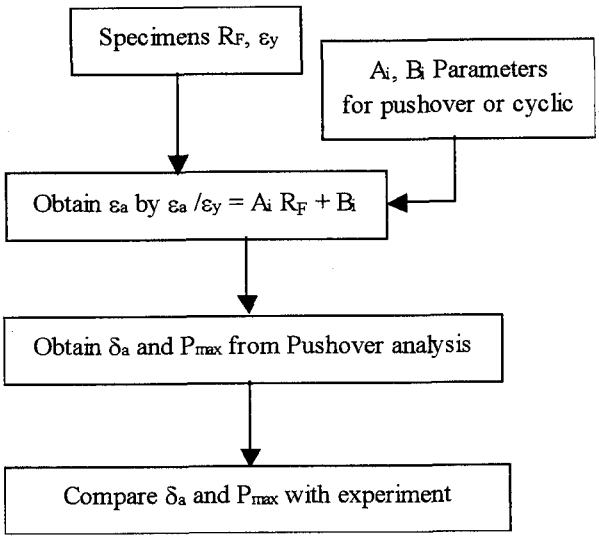

Fig.13 Flowchart of calculation of allowable displacement and maximum load for strain

Figure 14 shows the results for allowable displacement obtained from both pushover and cyclic regression lines. The results show that the calculated values lie within a degree of error of approximately 20% to that of experimental values. However, for pushover, the results are evenly spread around the 1:1 axis, whereas for cyclic results, the calculated values are skewed at an angle and unsafely lie off the 1:1 axis. As for maximum load results shown in Figure 15, the results indicate that the calculated values lie within an approximate 10% error margin. The reason for the increased accuracy occurs due to plateau effect exhibited around the allowable displacement. Similarly, the pushover results are evenly spread around the 1:1 axis while cyclic results are skewed.

8.2 Calculation by Curvature Results

The procedure was repeated for the analytical results obtained by curvature (as shown by the flowchart in Figure 16). By using the specimen parameters' of R_F and yield curvature in conjunction with the regression lines obtained for pushover and cyclic analyses, the allowable curvature can be obtained. Similarly, this result is termed the calculated allowable curvature. Using the calculated allowable curvature a corresponding allowable displacement and maximum load is determined from pushover analysis results. The plots of allowable displacement and maximum load in comparison with experiments are shown in Figures 17 and 18 respectively.

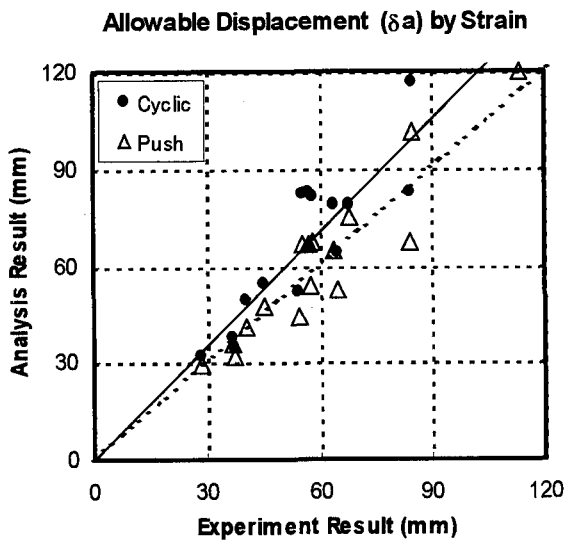

Fig.14 Allowable displacement as calculated by strain results

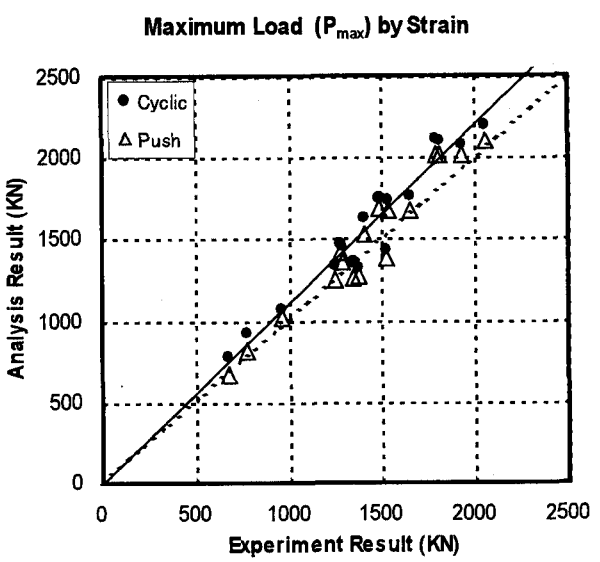

Fig.15 Maximum load as calculated by strain results

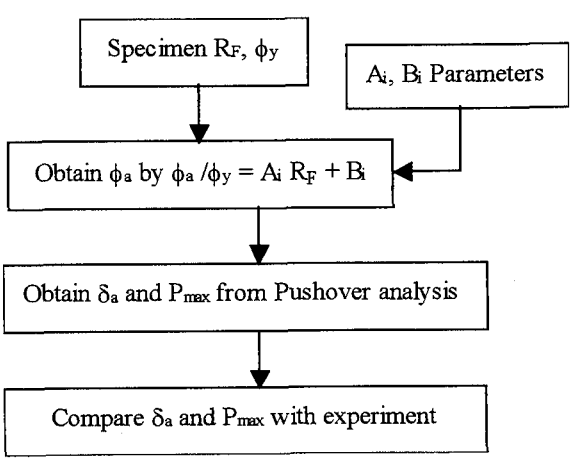

Fig.16 Flowchart of calculation of allowable displacement and maximum load for strain

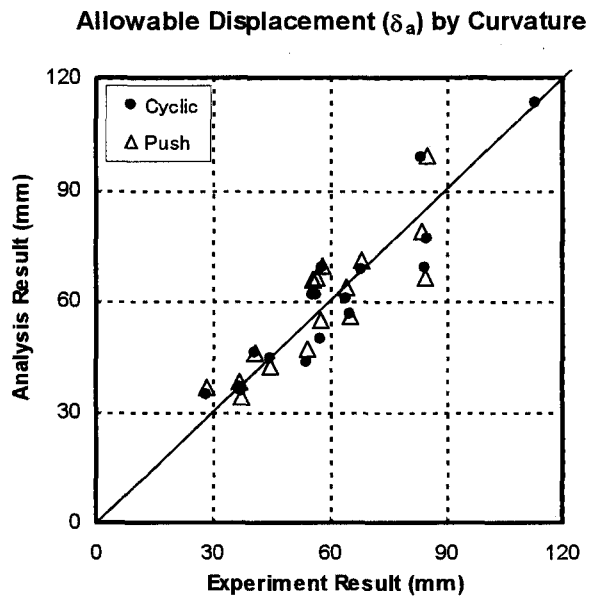

Fig.17 Allowable displacement as calculated by curvature results

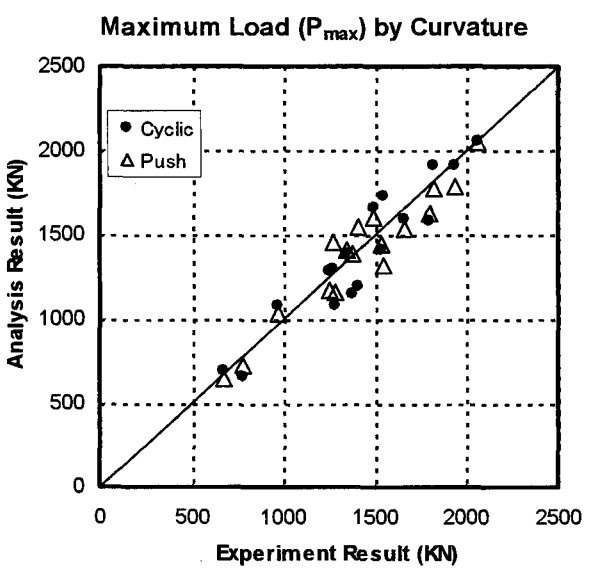

Fig.18 Maximum load as calculated by curvature results

The calculated results for curvature show a contrasting trend to that of for those results calculated by strain. Despite a similar error margin of 20% and 10% for allowable displacement and maximum load results respectively, the results for curvature of both pushover and cyclic loading pattern are both even spread around the 1:1 axis. This indicates that while strain is influenced by loading pattern, curvature is not affected at all. Thus using curvature to calculate the values of allowable displacement and or maximum load, using either a pushover loading pattern or a cyclic loading patterns the resulting calculated values would be consequently indifferent.

Whereas some authors prefer strain[12] as the seismic performance criterion, curvature is not influenced by loading pattern and thus has a significant advantage over strain in use with the fiber model[6,7].

9. Conclusion

In conclusion, this paper conducted pushover and cyclic analyses on 17 rectangular steel pier specimens using the fiber model. The purpose of this investigation was to determine the method of estimating the allowable displacement using the fiber model.

Firstly, the pier parameter, width-to-flange thickness ratio R_F, was determined as the best parameter to be used for correlation with both strain and curvature results due to a high correlation and its relative simplicity.

Next, strain and curvature were considered as criterions for calculating the allowable displacement of steel piers. Investigations were conducted into the influence of cyclic loading pattern and applied axial load to a pier on the two criterions of strain and curvature. These results show that the preferred criterion for estimating the allowable displacement of steel bridge piers is curvature since for both cyclic loading pattern and axial load investigation there exhibited no influence of curvature results while the influence on strain results were quite considerable.

In comparison with experimental results, the analytical result of maximum horizontal load showed a good agreement.

Lastly, an investigation was also conducted into the calculation of allowable displacement and maximum load through regression lines obtained from both strain and curvature results. The results show that the allowable displacement can be predicted within 20% error and maximum load within 10% error. However, for strain results, by plotting pushover and cyclic results simultaneously, it was shown that strain cyclic results are unsafe as the results are skewed off the 1:1 axis. However, for curvature the results for pushover and cyclic analyses remain symmetrical further indicating the

unique characteristic that curvature is uninfluenced by loading pattern.

As during an earthquake, the earthquake may take a multitude of forms it is prudent to choose use seismic performance criterions for which the result leads to a single value and hence independent of external loading. Curvature has such a unique nature and is hence preferred for the criterion for estimating the allowable displacement of steel bridge piers using the fiber model.

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ファイバーモデルを用いた鋼製橋脚の耐震性能評価手法

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本研究では、ファイバーモデルを用いた鋼製橋脚の耐震性能評価手法に関する検討を行った。非線形動的解析では耐震性能評価する指標として、ひずみおよび曲率に着目した。繰り返しと軸力の影響を考慮した上で、限界状態と仮定した許容変位と最大水平荷重の算出にひずみ規範を用いる場合と曲率規範を用いる場合との比較を行った。その結果、ひずみを用いると繰り返しや軸力の影響を敏感に受けるに対し、曲率は繰り返しや軸力の影響が少ないため、曲率の方が想定した限界状態を再現できることがわかった。最後に、ファイバーモデルを用いた解析結果を実験データと比較することによりファイバーモデルを利用したの耐震橋脚設計の妥当性を確認した。

キーワード：ファイバーモデル、許容変位、ひずみ、曲率