SECOND EUROPEAN CONFERENCE ON EARTHQUAKE ENGINEERING AND SEISMOLOGY, ISTANBUL AUG. 25-29, 2014

PREDICTIVE METHOD OF INELASTIC RESPONSE AND RESIDUAL DEFORMATION OF STEEL FRAME USING SEMI-RIGID CONNECTIONS WITH SELF-RETURNING RESTORING FORCE CHARACTERISTICS

Junya Yazawa [1] Seiya Shimada[2] and Takumi Ito[3]

ABSTRACT

Authors have proposed the semi-rigid connections with self-returning characteristics by use of spring washer or shape memory alloy bolt. And the monotonic and cyclic loading tests of this connection were conducted. It is observed that the test results showed self-returning characteristics of connections. And also, the restoring force characteristics model were assumed, furthermore the seismic response analysis was conducted by use of this model. And the horizontal loading tests of framework with semi-rigid connections with self-returning mechanisms were conducted to examine the inelastic behaviour of the whole framework. From these test results, these connections have the self-returning characteristics, however, the poor energy absorptions. So then, the structural system with moment resisting frame and braced frame to obtain the energy absorption mechanism is proposed. In this paper, the seismic resistant performance of the proposed structural system is investigated analytically.Then, to obtain the statistical distribution of analytical variables, the Monte Carlo simulations are conducted. From the analytical results, the structural system with combination of the frame with the semi-rigid connection and steel brace showed small residual response deformation. Furthermore, a prediction method of maximum and residual deformation is proposed. Finally, it is confirmed that the prediction of maximum and residual deformation shows a general sufficient accuracy.

1. INTRODUCTION

A semi-rigid connection by use of various types of fasteners and material has been applied in steel beam-to-column connections, replacing to a rigid joint by welding or high tension friction bolt. A large number of experimental and analytical studies have been conducted, and a seismic resistant performance of the steel structure having the semi-rigid connections has been investigated (Suita K., 2009).

Fujii and Ito et al., (2011) conducted monotonic and cyclic loading tests of semi-rigid connections by use of spring washers, and the test specimens of cantilever-columns were constructed and horizontally loaded to investigate the inelastic behaviour of the semi-rigid connections. The test results showed the self-returning characteristics of connections. From the test result, the restoring force characteristics model was assumed. The setup of this loading test as the cantilever test specimen is presented in Figure 1, that is, the bending deformation is occurred on the connections. Therefore, it is desirable that the whole behaviour of the framework with semi-rigid connections should be

[1] Tokyo Univ. of Sci., 6-3-1, Niijuku, Katsushika-ku, Tokyo, Japan, j4113657@ed.tus.ac.jp
[2] Tokyo Univ. of Sci., 6-3-1, Niijuku, Katsushika-ku, Tokyo, Japan, cosmicsource.dec16@gmail.com
[3] Tokyo Univ. of Sci., 6-3-1, Niijuku, Katsushika-ku, Tokyo, Japan, t-ito@rs.kagu.tus.ac.jp

confirmed experimentally. Yazawa et al. (2013) conducted the horizontal loading tests of framework test specimen with semi-rigid connections having self-returning mechanisms. From the comparison of test results and analytical results of inelastic behaviour of connections, it was confirmed that the proposed model as shown in Figure 2 can chase the test results.

In this paper, the inelastic response behaviour and seismic resistant performance of a single story steel frame model with a brace having this connection is verified, and the prediction method of maximum and residual deformation is proposed.

2. ANALYTICAL MODEL

2.1. Description of structural system of self-returning mechanism

Yazawa et al. (2013) showed the test results that the framework having this semi-rigid connection has poor energy absorptions. So then, the structural system with moment resisting frame and braced frame to obtain the energy absorption mechanism is proposed as shown in Figures 3, 4. İt is aimed that the mitigation effects of maximum deformation and energy absorption are obtained by steel braces, and the self-returning effect is obtained by restoring force characteristics of this connection.

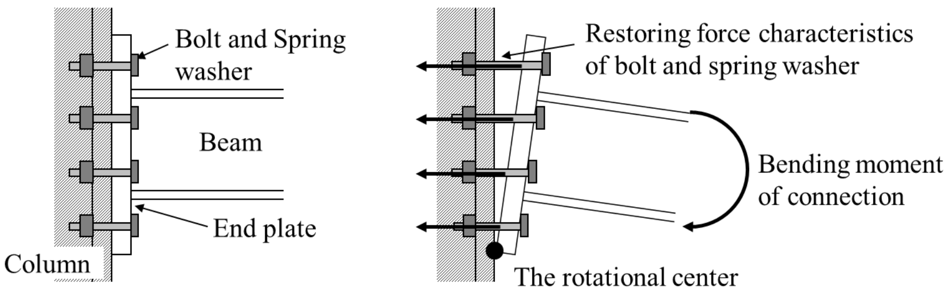


Figure 1. Resistant mechanism and behavior of semi-rigid connection by the extended end plate type

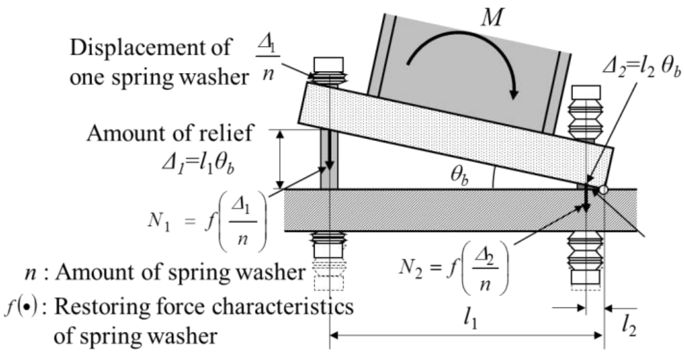


Figure 2. Analytical model of connection

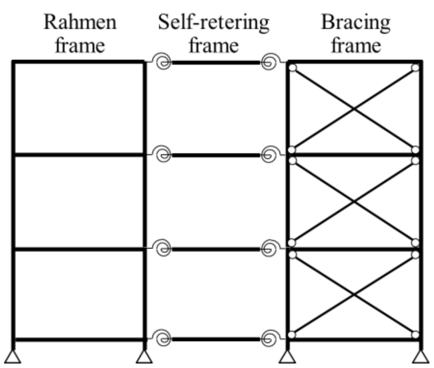


Figure 3. Structural system

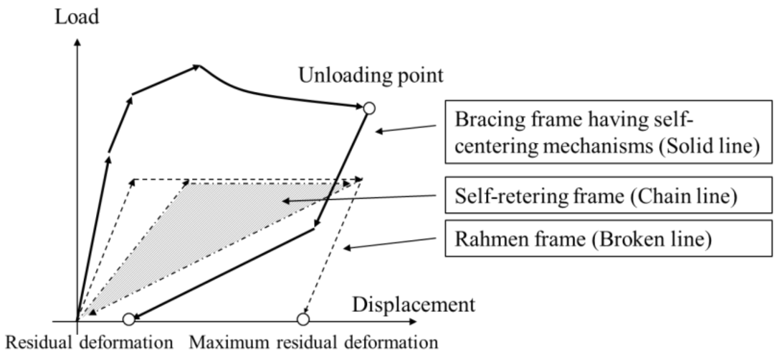


Figure 4. Restoring force characteristics of proposed steel frame

2.2. Single-story analytical model with steel braces installed

In order to verify the inelastic response behaviour and seismic resistant performance of the framework which has brace and the semi-rigid self-returning connections as shown in Figures 1, 2, a single-story model is adopted as shown in Figure 5. Then, the behaviour of structural systems with self-returning mechanism under the seismic motion is examined. The analytical frame model is pinned support at column base, and it is assumed that a column (H-250x250x9x24, SS400 (Grade of Japanese Industrial Standard)) and a beam (H-250x125x6x9, SS400) behave within elastic, so then the beam-to-column connection as shown in Figures 1, 2 show the inelastic behaviour. It is assumed that the inertial mass is 9,000kg and damping factor is 2% of this frame. Full plastic moment of the column is larger than that of the beam. A natural period of framework is determined from the inertial mass and an initial stiffness of the whole framework. And, the P-Δ Effect is not considered herein.

2.3. Restoring force characteristic model of self-returning connection

A model of semi-rigid connection using spring washer as shown in Figure 6 is applied for a restoring force characteristic of this connection (Fujii H, Ito T, et al., 2011). An elastic rotational rigidity of the skeleton curve of the connection is decided by a fixation degree. The fixation degree is expressed as a ratio of the moment of the semi-rigid connection to the moment of a rigid connection. As shown in Figure 7, when eight spring washers are adopted, the fixation degree of the connection with a series type is 0.29, and the fixation degree of a series-parallel type is 0.45. Herein, the case of the connection of series-parallel type is studied. And a maximum bending moment of semi-rigid connection is adjusted to equal value of full plastic moment M_{pb} of the beam.

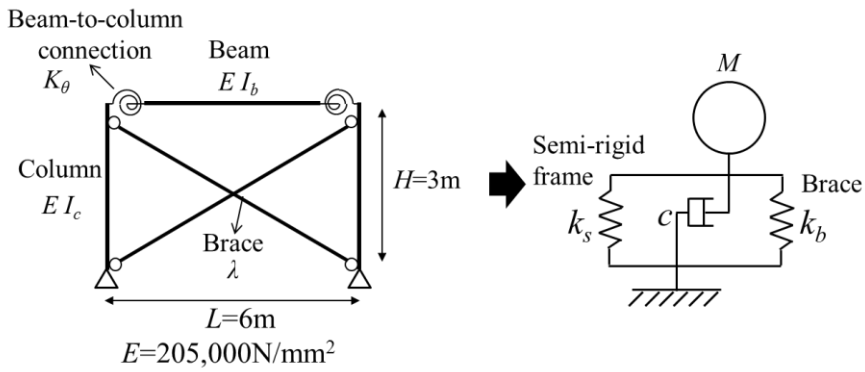


Figure 5. Analytical frame model

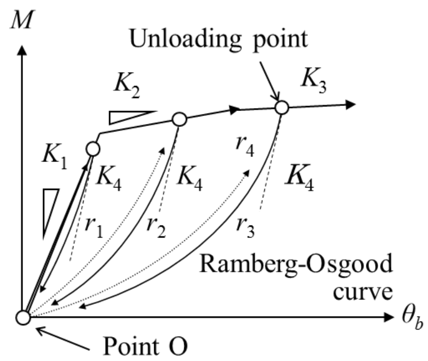


Figure 6. Model of semi-rigid connection

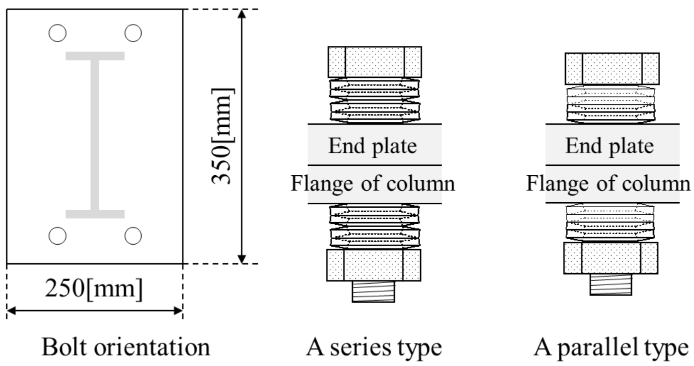


Figure 7. Pilling direction and stack-type of spring washer

2.4. Restoring force characteristic model of steel brace

By the reference of an enormous past test data of steel brace under cyclic loading, a restoring force characteristic model of brace member has been formulated (Shimoda Y, Ito T., 2010). This model is based on the Wakabayashi model (Wakabayashi M, Shibata M., 1982). Figure 8 shows hysteretic behaviour of two different types of steel brace which slenderness ratio is 20 and 80. The strength of framework having semi-rigid connection and the steel brace is decided by the lateral resistant strength shear ratio of brace β as shown in figure 9. In this paper, the value of β is considered to be 0.6.

3. INPUT GRAOUND MOTION

To obtain the statistical distribution of seismic response and performance, the Monte Carlo simulations are conducted. Therefore, thousand simulated input motions are generated artificially which have certain phase characteristics such as a short range motions and an oceanic motions (Kuwamura H., Iwata Y., (2002)). And the Fourier amplitude spectrum of simulated input motion is assumed as shown in Figure 10. Herein, the duration of earthquake motion is 32.77 seconds (time interval is 1/500 seconds) and it has the enough time for free vibration after main dynamic part in order to acquire residual deformation. The examples of the time-history of artificial simulated input motions are shown in Figure 11. The maximum amplitude of input motion is determined as follows: $D_s = Q_u / Q_e = 0.5$, where $Q_e = M\ S_A$ (S_A is an acceleration response spectrum) is elastic response shearing-force, and Q_u is the ultimate lateral strength of frame.

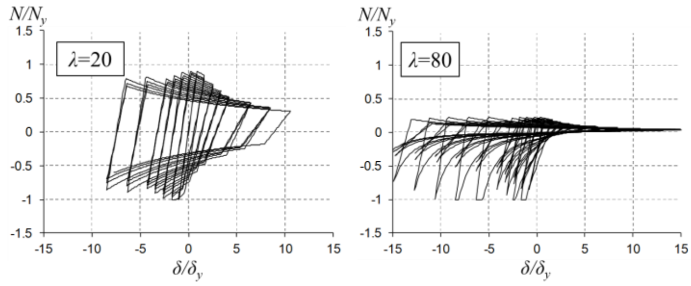


Figure 8. Hysteresis behaviour of brace members

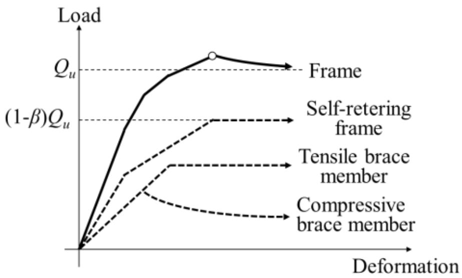


Figure 9. Relation of skelton curve

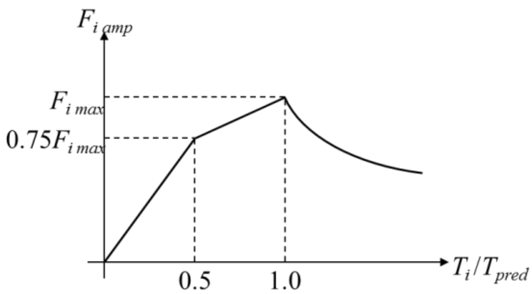


Figure 10. Fourier amplitude spectrum

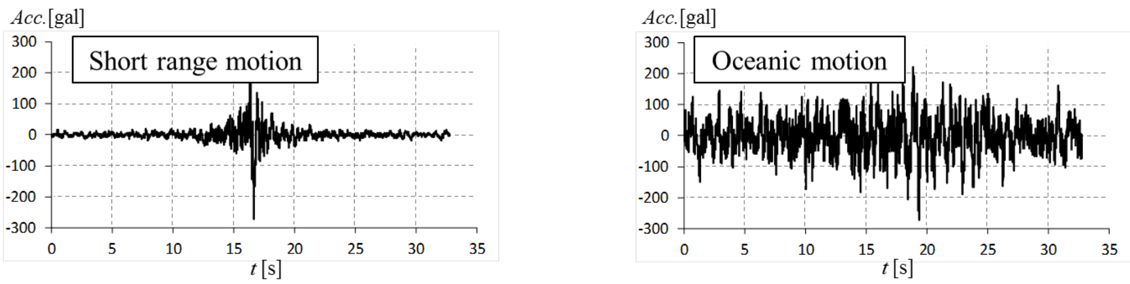


Figure 11. The example of the time history of artifical simulated earthquake motion

4. HISTOGRAM OF RESPONSE AGAINST TO SIMULATED EARTHQUAKE INPUT MOTION

4.1. Results of maximum and residual deformation

From the response analysis, the histogram of an absolute value of a maximum deformation θ_{max} and a residual deformation θ_r are acquired as shown in Figure 12. The maximum deformation θ_{max} is slightly large, and a ductility factor of moment resisting frame having semi-rigid connection become up to around 4 and the brace become up to 10. It is confirmed that residual deformation is small on the whole. By the comparison of the short range motion and the ocean motion, the dispersion in maximum deformation becomes small, and the dispersion in residual deformation becomes large. In the case of the short range motion, it is unexpected that the steel brace is enough energy absorption. On the other hand, during the free vibration after the main dynamic part, the rigidity of brace does not decrease. However, it is considered that residual deformation remains easily in case of small slenderness ratio. In the case of the oceanic motion, the residual deformation becomes small because the rigidity of brace is deteriorated.

4.2. Results of ratio of energy and deformation

In this paper, the histograms of a ratio of a maximum potential energy W_e of an elastic system to an potential energy W_p of an inelastic system (It is written as the ratio of the energy as follows) and a ratio of a maximum deformation θ_r of the elastic system to a maximum deformation θ_p of the inelastic system (It is written as the ratio of the deformation as follows) are examined. In the rigid joint framework using a restoring force characteristic of elasto-plastic model as shown in Figure 13, the histograms of the ratio of energy and the ratio of deformation are acquired, and the analytical results are shown in Figure 14. Herein, the Young's modulus E and the geometrical moment inertia I of a column and a beam are taken as equal to the framework having semi-rigid connections. In a small natural period range, a mean of the ratio of energy becomes close to 1. On the other hands, in a large natural period range, the mean of the ratio of the displacement becomes close to 1.

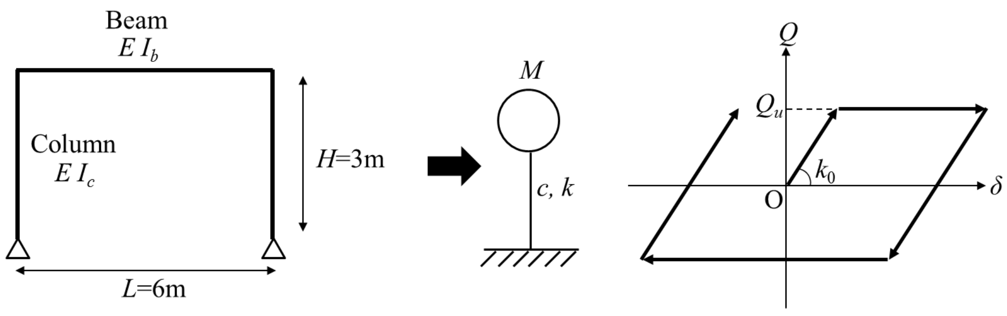


Figure 13. Analytical model of rigid joint frame

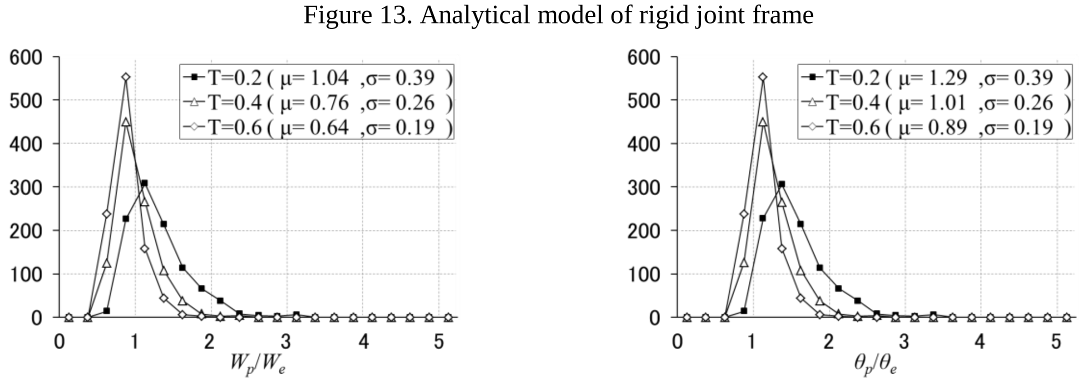
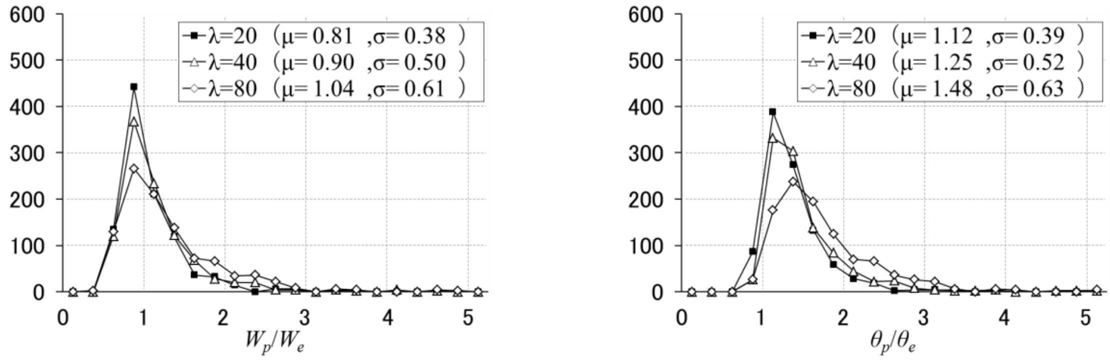


Figure.14 Histogram of ratio of energy and ratio of deformation

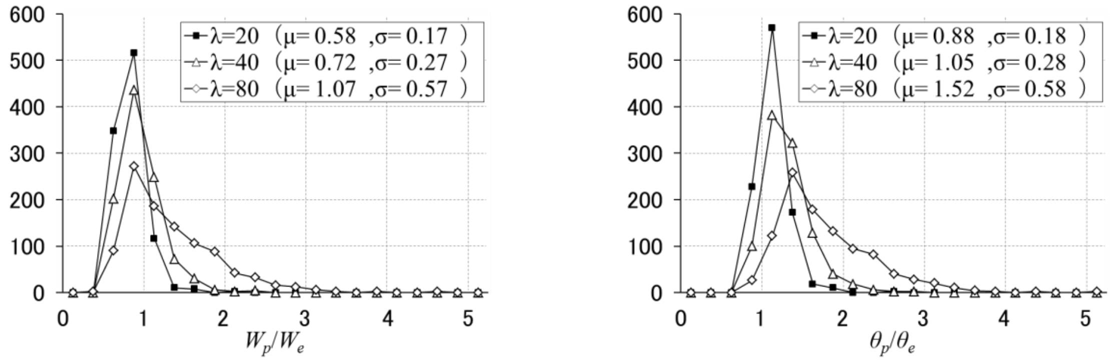
As mentioned above, it is confirmed that the former follow the property of energy conservation, and the latter follow the property of displacement conservation. It becomes an index to consider whether prediction methods are appropriate by the above. From the response analysis, in case of the framework having the semi-rigid connections, the histogram of the ratio of the energy and the ratio of the displacement is acquired as shown in Figure 15. From the result of Figure 15, the mean of the ratio of the energy and the ratio of the displacement become close to 1, and it is confirmed that the property of energy conservation and the property of displacement conservation are applicable.

4.3. Results of rate of residual deformation

The results of histogram of residual deformation rate (residual deformation/upper bound value of residual deformation) are acquired as shown in Figure 16. From the results of Figure 16, the effect of the fixation degree to the standard deviation of the residual deformation rate is small, and it is observed that the influence of the lateral resistant strength shear ratio of brace to the self-centering frame β and the slenderness ratio of brace member λ is large. Moreover, it is observed that the figure of histogram shows near the normal distribution.

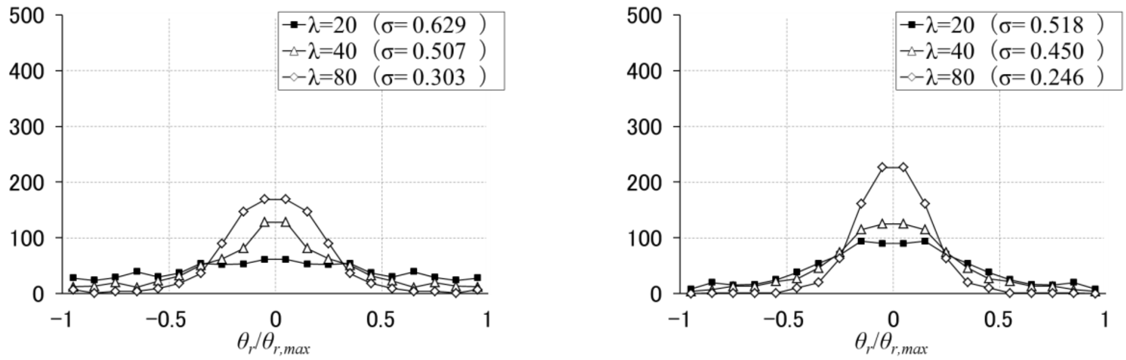


(a) Short range motion



(b) Ocean motion

Figure 15. Histogram of ratio of energy and ratio of deformation



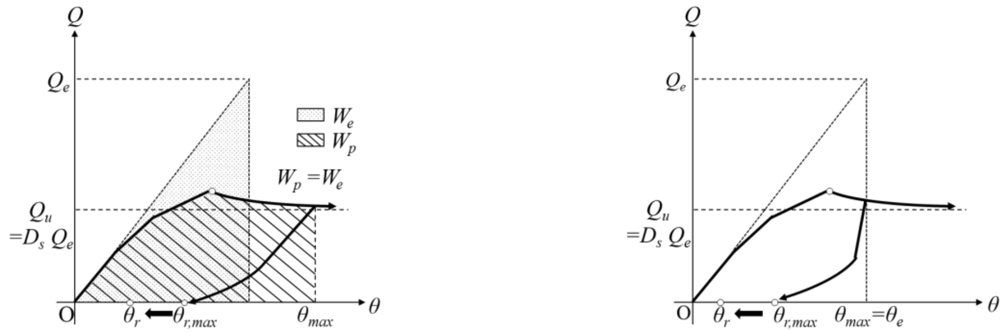
(a) Short range motion (b) Ocean motion

Figure 16. Histogram of rate of residual deformation

5. PREDICTION METHOD OF RESIDUAL DEFORMATION

5.1. Flow of prediction method of residual deformation

From the result of Figure 15, the mean of the ratio of the energy and the ratio of the displacement become close to 1, and it is confirmed that property of energy conservation and property of displacement conservation are applicable. Then, a prediction method of a maximum response and the residual deformation are proposed by use of pushover analysis. The model of the prediction method for residual deformation is shown in Figure 17. The property of energy conservation and the property of displacement conservation are assumed, and the predicted value of the maximum response is acquired. First, an upper bound value of the residual deformation obtained from the predicted value of the maximum response by unloading. Second, the predicted value of the residual deformation is calculated from the relation of the above mentioned residual deformation rate. In addition, the residual deformation rate is assumed a value of 1σ of the histogram of each analysis model.



(a) Property of energy conservation (b) Property of displacement conservation

Figure 17. Prediction method of residual deformation

5.2. Verification of accuracy of prediction method

Examples of a relation of the time history of a story drift angle vs. the predicted value are shown in Figure 18. From the above, it is confirmed that the maximum deformation and the residual deformation can be predicted with in general sufficient accuracy by the proposed prediction method in this paper. Using the histogram of the residual deformation, the histogram of the absolute value/predicted value of the residual deformation can be calculated, and the chart figure of the mean and standard deviation is shown in Figure 19. It expresses that prediction is so difficult that standard deviation is large, and in the case of short range motion or the value of λ is large corresponds to this. In addition, the means become less than 1 with most cases. It is thought that the prediction of the residual deformation by the method proposed in this paper is in general appropriate as a result of figure.

6. CONCLUSIONS

The main conclusions of this paper are:

1) The maximum response and the residual deformation are reduced by the framework which used this connection and the brace.
2) From the analytical result of the histogram of the ratio of the energy and the ratio of the displacement, this evaluation index can examine the applicability of the property of energy conservation and the property of displacement conservation.
3) The prediction method of residual deformation using the property of energy conservation and the property of displacement conservation was proposed. From the analytical result, it is confirmed that the residual deformation can be predicted with in general sufficient accuracy by the proposed prediction method in this paper.

REFERENCES

Suita K, (2009) “Recent Experiments for Development of New Steel Joint System”, *Annual Meeting of Architectural Institute of Japan*, Tohoku, Japan, pp.4-15

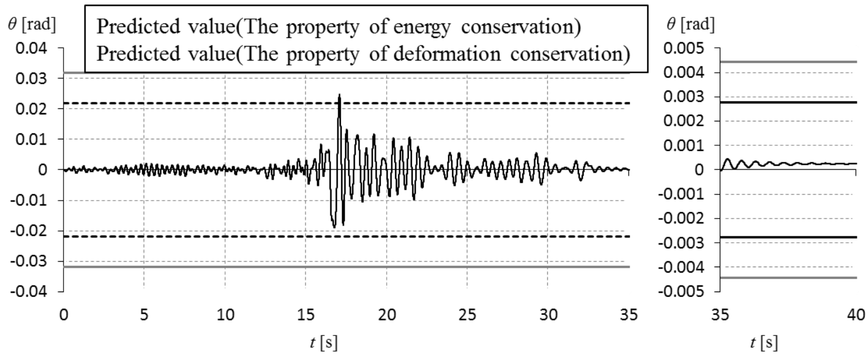
Fujii H, Takumi Ito, Kazuki Takahashi, Wataru Kambe, (2011) “An Experimental Study on Restoring Force Characteristics of Semi-rigid Connections by Use of Spring Washers”, *The 6th International Symposium on Steel Structures*, Korea

Yazawa J, Seiya Shimada, Takumi Ito, (2013) “ An analytical model of frame considered about deformation of connections”, *Annual Meeting of Architectural Institute of Japan*, Kanto, Japan, pp.537-540

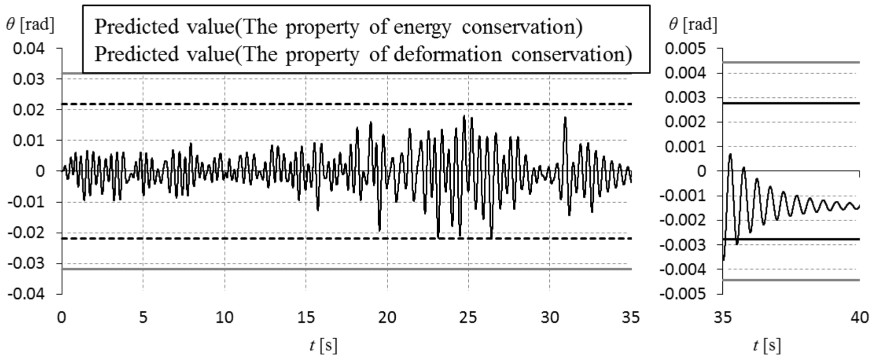
Shimoda Y, Ito T., (2010). “Database of strength and ductility of steel compression members subjected to cyclic loading, part 1”. *Annual Meeting of Architectural Institute of Japan (in Japanese).* pp.441-444.

Wakabayashi M, Shibata M., (1982). “Mathematical expression of hysteretic behavior of braces, part 1”. *Transactions of the Architectural Institute of Japan.* Volume 316, pp.18-24.

Iwata Y, Kuwamura H., (2002) “Earthquake input motions in performance evaluation of steel buildings structures Part2, Part3”. Research Report in Annual Meeting of Architectural Institute of Japan (in Japanese). 133-140

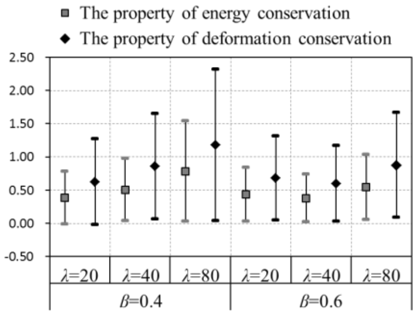


(a) Short range motion

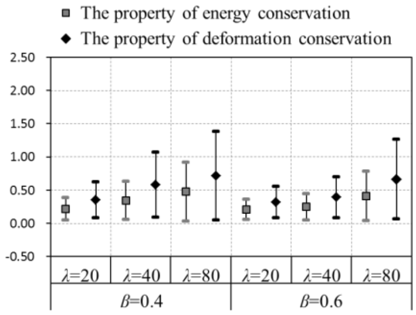


(b) Ocean motion

Figure 18. The time history of a story drift angle and the predicted value (λ=80)



(a) Short range motion



(b) Ocean motion

Figure 19. The chart figure of average value and standard deviation