SEISMIC UPGRADING BY PRECAST CONCRETE BRACE WITH ENERGY DISSIPATING FRICTION JOINT

Yutaka OSANAI[1] And Fumio WATANABE[2]

SUMMARY

Upgrading of seismic performance of existing buildings can be achieved by several methods such as steel or carbon fibre jacketing of columns, construction of new walls and/or braces and so on. A proposed method in this study is the upgrading by prestressed concrete diagonal brace for the perimeter frame of original building. Reversed V shape prestressed concrete brace is produced at the precast concrete factory and transported to the site. Then the top of the brace is connected to the upper beam at the centre span by the energy dissipating friction joint. The bottom ends of brace are fixed to the both ends of the lower beam by post tensioning. Static loading test on friction materials (granite plate), static and dynamic lateral loading tests on portal frames strengthened by the brace were conducted to investigate the efficiency of this upgrading system. Based on the experimental and analytical studies the seismic upgrading guideline for this newly proposed system was established.

INTRODUCTION

Many of existing reinforced concrete buildings does not meet the structural seismic performance required by the current regulations in Japan. During the 1995 Kobe Earthquake several such building suffered serious structural damage and many lives were lost. Therefore the assessment of seismic performance and upgrading of existing buildings are the most important issues to guarantee the safe human environment. After the Kobe Earthquake, seismic upgrading of existing building structures has been put in force, especially for public buildings such as schools and hospitals. Popular methods are jacketing of columns with steel pipe or fibre materials, steel bracing, new construction of reinforced concrete walls, installation of concrete lattice elements and so on. However, the bracing method by precast concrete elements is not well established.

In the seismic retrofitting work, several conditions arises as

1) Construction period should be short. For example, construction work of school buildings should be completed during the summer vacation (at least less than one month).

2) Construction work outside of the building is better than inside work to minimize the transportation of construction materials and machinery into the building, and to make the construction under service condition possible.

3) Increase of building weight is not excessive in order to use the existing foundation.

4) After the retrofit, ventilation, lighting and visual field should be ensured.

This report proposes the external brace by precast prestressed concrete diagonal elements using energy dissipating friction joint. To establish the design method for seismic upgrading, the static tests of friction materials, static seismic loading tests on frame and dynamic shaking table tests on frames were conducted.

[1] *Chief Engineer, Technical division, Oriental Construction Company, Tokyo, Japan*
[2] *Professor, Department of Architecture and Architectural Systems, Kyoto University, Japan*

SPECIFIC FEATURE OF PROPOSED METHOD

Seismic upgrading by steel brace has been widely used in several countries. The most popular method in Japan is the installation of steel frame with diagonal elements into original reinforced concrete frame. The steel frame is connected to boundary beams and columns with stud volts and cement mortar to ensure the shear transfer.

However this method has several disadvantages such as the damage to peripheral beams, columns and reinforcing bars. The long construction period due to troublesome manufacturing process and the noise of drilling are also drawbacks. The reinforced concrete brace also has some problems such as the unexpected

damage to original frame due to remarkable stiffness change of diagonal elements in tension and the brittle compression failure of diagonal elements. To avoid these disadvantages a new bracing system was developed.

The proposed bracing system consists of the prestressed concrete diagonal brace and the friction joint. The role of friction joint is to dissipate seismic energy and to control the input axial forces to diagonal elements to avoid the stiffness change due to cracking and to avoid the crushing of diagonal elements.

PRECAST PRESTRESSED CONCRETE BRACE SYSTEM

Pre-cast concrete diagonal elements are produced at the factory and prestressed by post tensioning. The role of prestressing is to give higher tension cracking strength of diagonal element. A unit brace has a reversed V shape with two diagonal elements and connected to perimeter frame of a building as indicated in Fig. 1.

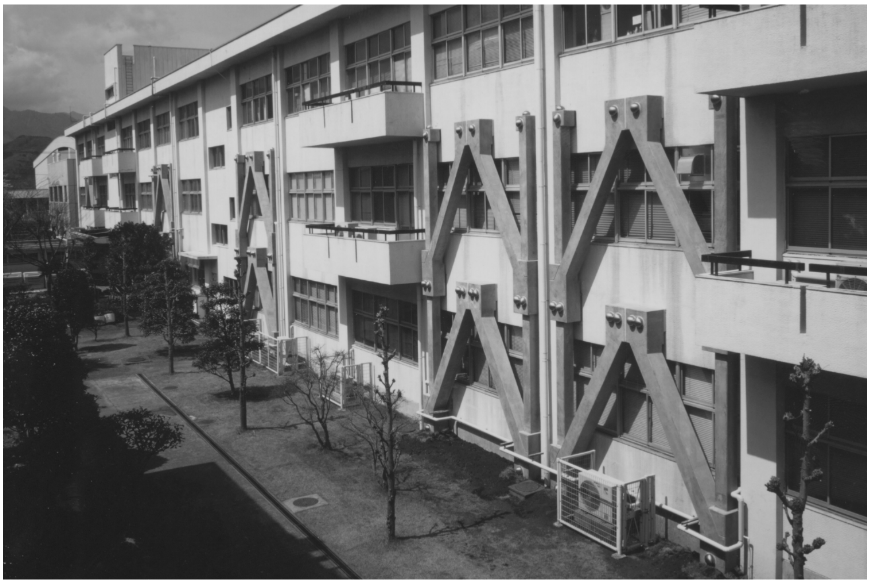

Fig.1 photo of installed PCa brace on peripheral frame

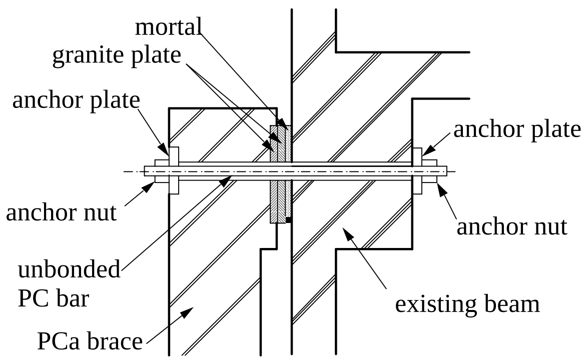

Fig.2 friction joint connected to upper beam

The top of a brace is connected to the centre of an upper beam through friction controlled joint. Detail of friction controlled joint is indicated in Fig. 2. The joint consists of two granite plates and a connecting prestressing bar. The product of friction coefficient of materials and prestressing force gives the maximum friction resistance.

Therefore the expected friction resistance (the maximum input force to brace) is easily realized to choose an appropriate binding force by prestressing. The friction coefficient between two granite plates depends on the slip deformation and is given based on the test results (equation (1), (2):Chapter4) When the lateral force induced to a brace exceeds the friction resistance of the top connection, the slip deformation occurs and the lateral resistance of a brace is kept constant. This means that the axial tension force induced to diagonal concrete element can be kept constant less than cracking load.

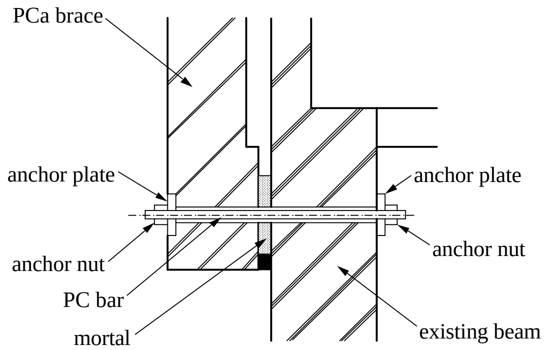

Fig.3 fixed joint connected to lower beam

Bottoms of two legs of a brace are fixed to the both ends of lower beam by post tensioning as indicated in Fig. 3. Prestressing force is selected large enough to avoid the slip, where the friction coefficient for the interface between joint mortal and concrete is assumed to be 1.4.

Energy dissipation at the friction joint is achieved by the friction damping. The restoring force characteristics of joint show bi-linear behavior with high stiffness in a first branch and small positive stiffness in the second branch. Therefore the hysteretic loop has almost rectangular shape.

At the top of a brace, only lateral force transfer is considered because the axial tension and the axial compression in diagonal elements can be cancelled where the axial deformation of diagonal element is very small and can be ignored. At the bottom end of a brace, tension and compression force induced to beam end sections should be resisted by beam shear. Therefore when the direct shear strength at beam end section is not enough, extra columns are constructed to sustain the diagonal force from the brace elements.

The sectional area of prestressing steel in a concrete brace is chosen to be able to resist 1.3 times axial force required in design for some reserve strength. Therefore when the unexpected large lateral seismic force is induced to the brace, prestressing tendon may not be torn off.

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TEST OF FRICTION MATERIALS AND BRACED FRAMES

Loading tests on friction materials and braced frames were conducted to determine the friction coefficient and to investigate the seismic performance brace system.

Friction tests of granite plate

Preliminary friction tests were conducted on several friction materials (marble, granite and high strength concrete) with several surface conditions. Then the granite with natural cut surface was chosen as the friction materials. Push-off shear tests were conducted using granite columns with 100x100mm square section and 200mm high in side columns and with 100x100mm square section and 300mm high in central column. Three granite columns were arranged side by side and binded laterally with constant load of 100KN (normal stress at the interface is 5 KN/mm^2). Monotonic and cyclic shearing force was statically applied to a central column as indicated in Fig.4. Test results are summarised on Table 1.

Typical example of load slip relationship is indicated on Fig.5. Measured friction coefficient at first slip scattered within a range from 0.34 to 0.64 (average value was 0.46). As the increase of slip deformation, the friction coefficient increased and tend to constant value beyond the slip of 10 mm in all specimens (average value was 0.73).

The friction coefficient between two granite plates depends on the slip deformation. Therefore the design values of friction coefficient for seismic design were determined as follows.

(1) At first slip: friction coefficient=0.40
(2) Beyond 10mm slip: friction coefficient=0.65
(3) Between them : friction coefficient is given in relativity to slippage from 0.4 to 0.65

For the design of prestressing force of concrete brace, the friction coefficient is assumed to be 0.85 to give some safety margin for tension cracking.

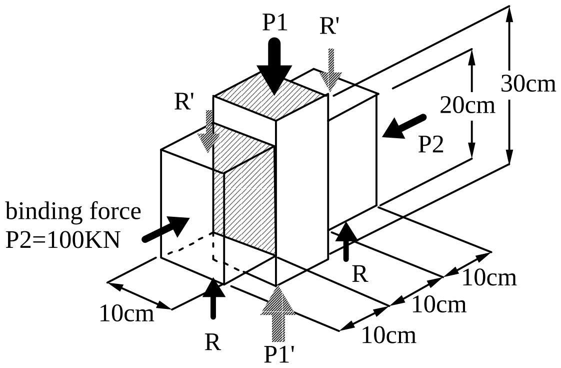

Fig.4 Friction tests of granite columns

Table1 Friction test result

stage	at first slip	beyond 10mm slip	maximum load
load(kN)	93.4	150.0	157.0
binding force(kN)	101.4	102.2	102.1
average of friction coefficient	0.46	0.73	0.77
scattering of friction coefficient	0.34~0.63	0.71~0.76	0.74~0.79

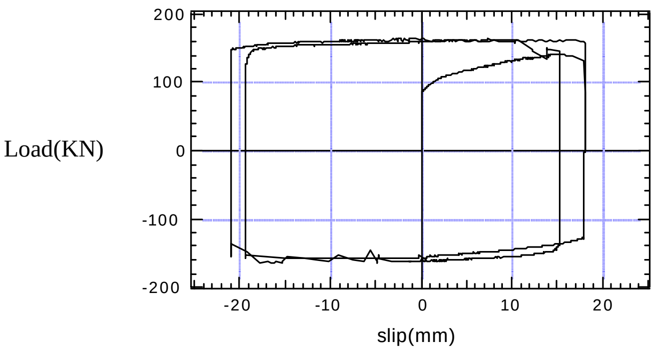

Fig.5 load slip relationship of granite

Lateral seismic loading test on a reinforced concrete frame with brace

A half scaled reinforced concrete portal frame with span length of 3.2 meter and height of 1.9 meter was constructed (Fig.6).

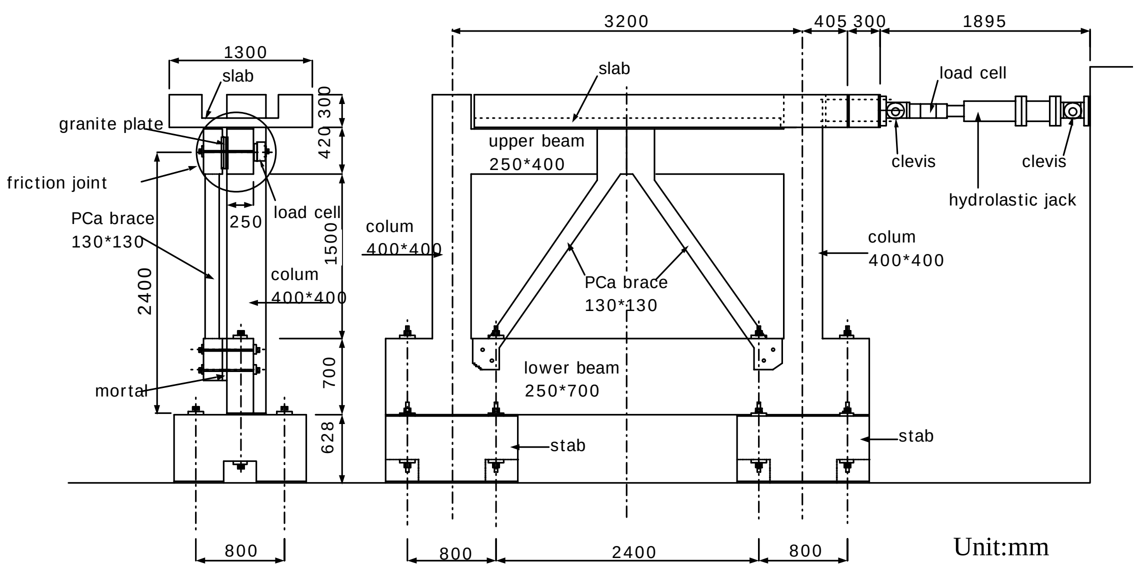

Fig.6 lateral seismic loading test

Then the concrete brace was attached to the side of a frame. Two granite plates were used as the friction material with initial binding load of 148KN. Section of concrete brace was 13.0x13.0cm square and prestressed at 60KN. Calculated tension cracking strength of concrete brace is 129 KN.

Obtained load deflection curve was indicated in Fig.7. At the lateral load of 90KN, flexural cracking at column bottom section and the slip at friction joint observed showing the reduction of lateral stiffness.

Flexural yielding of column bottom section occurred at the load of 330KN and the considerable reduction of stiffness was observed. However the stiffness kept positive and no any reduction of load carrying capacity was observed up to 2 % drift. The load increase from 1 % to 2 % drifts is due to the increase of binding force at the friction joint. During the test no any tension crack was observed in the concrete diagonal elements. Load deflection curve was computed by non-linear two-dimensional analysis and indicated in Fig.7. In the analysis, friction coefficients given by equation 1 and equation 2 were used. Result showed the good agreement to experiment.

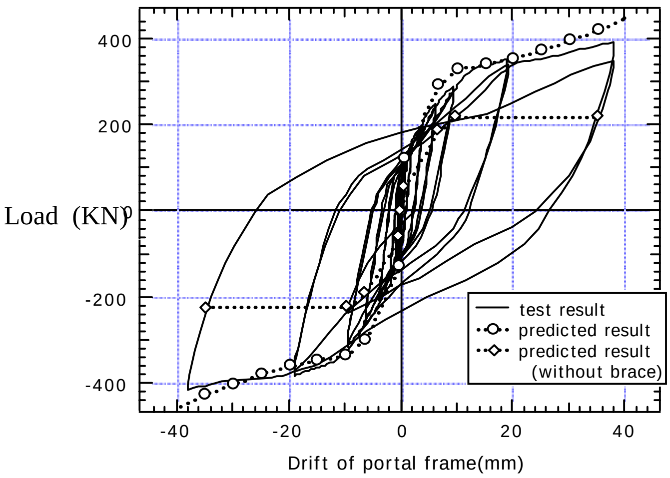

Fig.7 load deflection curve

Shaking table tests of brace system

To investigate the dynamic behavior of the brace system, shaking table tests were conducted on two portal frames strengthened by the concrete brace. Details of tested frame were indicated in Fig.8.

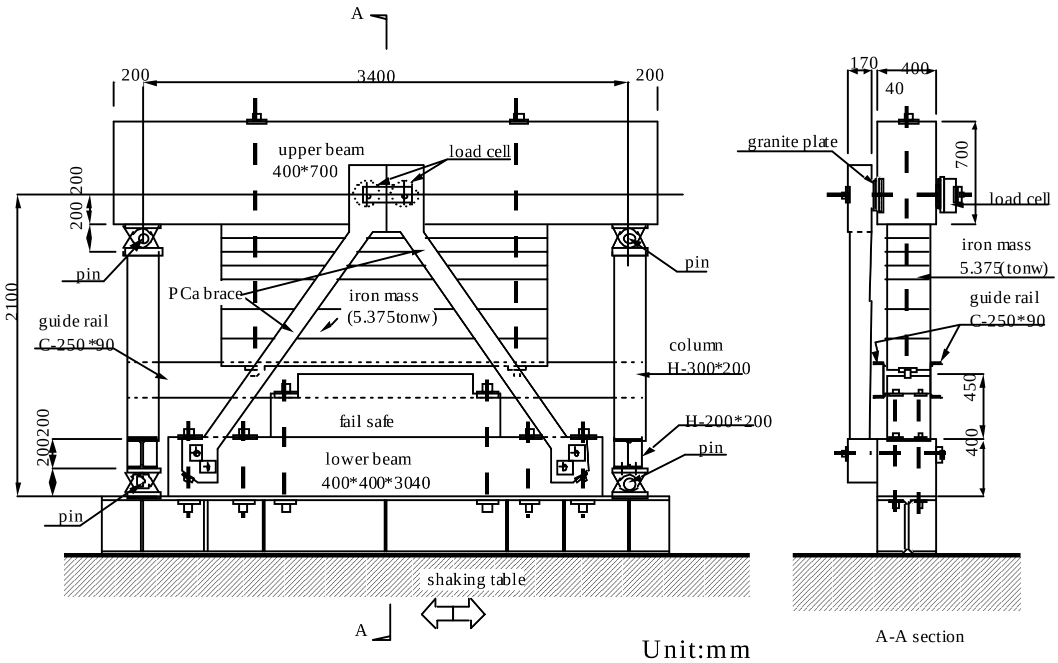

Fig.8 shaking table tests

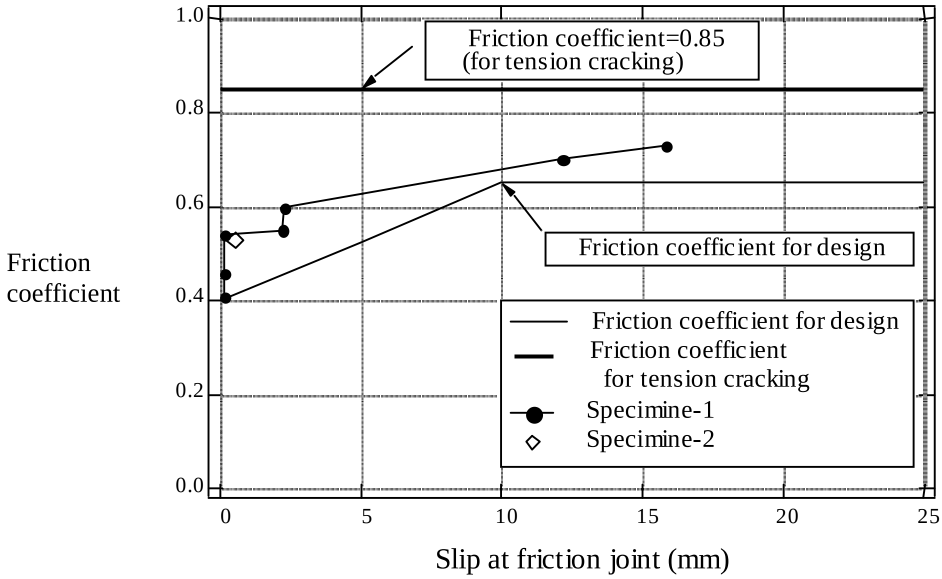

Fig.9 comparison of design friction coefficient and observed friction coefficients

Tested frames consist of reinforced concrete top beam, reinforced concrete foundation beam and steel columns. Two steel columns connected to top and bottom beams with pin joints. The top of the brace was jointed to upper beam through friction joint of two granite plates and the bottom was fixed to foundation beam. Therefore the inertia force during the shaking test is only resisted by concrete brace through friction joint. The heavy iron mass is put below the upper beam. Section of concrete brace was 13x13cm square and prestressed at 60KN. Calculated tension cracking strength of concrete brace is 136KN. Each specimen was tested under several levels of sinusoidal waves and recorded earthquake waves. The maximum input acceleration was 1300 gal.

Differences between two specimens are only the binding force at the friction joint. Specimen-1 with ordinary binding force at friction joint (158KN) is expected to show the predicted slip behavior and energy dissipation without any damage to concrete diagonal elements. Predicted maximum friction resistance at top joint was 115KN (0.73x158KN).

For Specimen-2, larger binding force of 373 KN was applied, where the damage to concrete diagonal elements was expected to unexpected large input acceleration. Predicted maximum friction resistance was 272KN (0.73x373KN).

Design friction coefficient based on the static tests and observed friction coefficients compared in Fig.9. The friction coefficient at the first slip of Specimen-1 was larger than 0.40 and gradually increased as the increase of deflection response. Beyond the deflection of 10 mm, the friction coefficient exceeded the design value of 0.65. Observed maximum value was 0.73 and did not exceed 0.85. Specimen-2 also showed similar values of friction coefficient.

When the response acceleration of Specimen-2 showed 1600 gal., the tension force of concrete brace and reached at 113 KN. It didn’t exceed the cracking strength of 136KN. The tension crack was not observed. At the acceleration response of 2460 gal., the tension force of concrete brace exceeded the cracking strength and reached 174.1 KN. Little tension crack was observed. However the damage to concrete brace was very slight.

During the shaking tests, the binding force at friction joint was slightly increased as the increase of deflection response. The increment was 1.9 KN when the specimen-1 responded at the deflection of 5.7 mm where the input acceleration was 1200 gal. For specimen-2, it was 2.0 KN at the deflection response of 2.1 mm where the input acceleration was also 1200 gals. The maximum increments of binding force of specimen-1 and specimen-2 were 3.5 KN and 5.4 KN, respectively. From this results it is stated that the increment of binding force can be ignored for design purposes.

CONCLUSION

The features of this seismic upgrading method are

1) Large hysteretic energy dissipation can be expected at the friction joint,

2) Seismic lateral force to be resisted by prestressed concrete brace can be controlled by the magnitude of the post tensioning force at the connection and

3) Cracking of concrete diagonal brace can be avoided by selecting an appropriate combination of prestressing force in bracing members, friction materials (friction coefficient) and binding force at sliding connection.

Obtained results can be summarized as

1) Friction coefficient of granite-to-granite interface is from 0.4 to 0.7 and depends on the sliding displacement regardless of loading rate.

2) This bracing system can largely enhance the seismic performance of reinforced concrete portal frame without cracking in bracing member