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Innovative Seismic Retrofit Technique for Existing RC Buildings Using External Corrugated Steel Plate Walls

A. Hamada [(1)], T. Fukuhara[(2)], H. Ikeda[(3)], N. Kondou[(4)]

[(1)] *Takenaka Corporation, Tokyo, Japan, hamada.akitoshi@takenaka.co.jp*
[(2)] *Takenaka Corporation, Tokyo, Japan, fukuhara.takeshi@takenaka.co.jp*
[(3)] *Takenaka Corporation, Osaka, Japan, ikeda.hidemi@takenaka.co.jp*
[(4)] *Takenaka Corporation, Osaka, Japan, kondou.naoto@takenaka.co.jp*

Abstract

In Japan, strengthening by steel braces has been one of the common seismic retrofit techniques for vulnerable existing RC buildings. Generally, the implementation of existing retrofit techniques alters external buildings' original design, and steel braces are not an exception. Therefore, this paper proposes a new retrofit technique that deals with the seismic aspect by providing the retrofitted building with sufficient seismic capacity and, at the same time, it provides existing buildings with a vitalized exterior design without altering neither the location nor the size of windows. The proposed retrofit technique uses corrugated steel plate walls within steel frames. These steel frames are installed externally to existing RC buildings and connected to their RC beams using mechanical anchors. Furthermore, this technique enables designers to overhang balconies, which may serve as solar shadings and natural drafts. The seismic performance of the proposed retrofitting was confirmed by experimental test under simulated seismic loading. The structural experimental test was conducted on a single one half scale specimen, representative of existing RC frames. The one-story one-span specimen was composed of two columns and two beams simulating a part of a frame. This paper reports the retrofit process of the proposed technique and its features, the related experimental test results and an outline of the first project where the proposed new retrofit technique was applied.

Keywords: seismic retrofitting, external strengthening, corrugated steel plate wall, renewal of exterior design

1. Introduction

1.1 Back ground

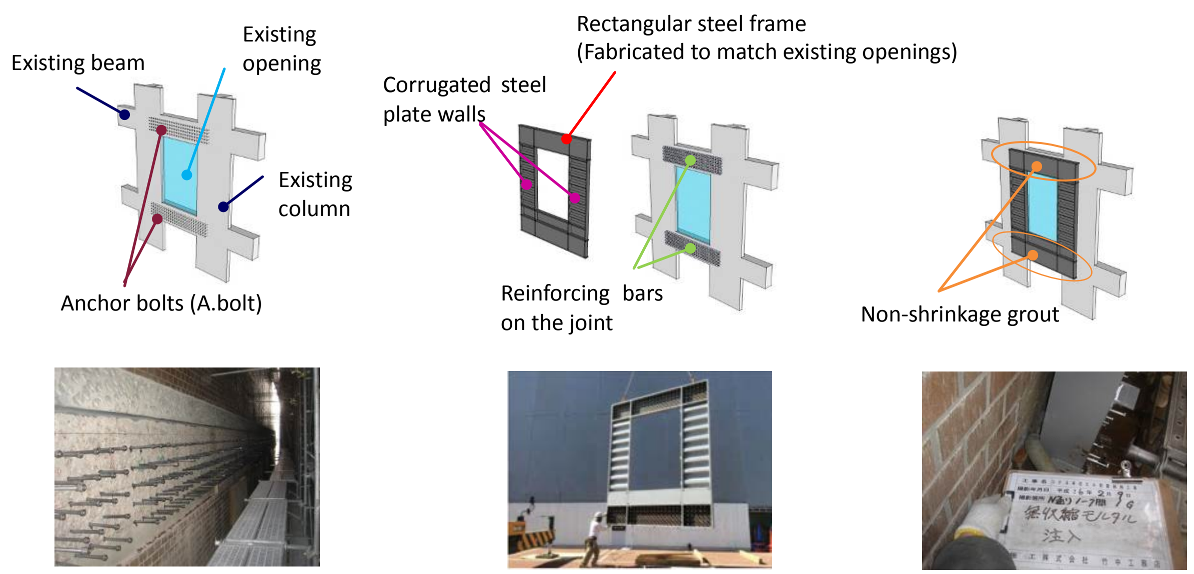
In earthquake-prone Japan, seismic design regulations have been amended after each large-scale earthquake occurrence, especially in 1980 where the law was thoroughly revised and took effect in 1981. Since then, standards and guidelines for seismic evaluation and retrofit methods have been prepared and continuously revised by Japan Building Disaster Prevention Association (JBDPA, 2001), (JBDPA, 2009). As a result, seismic performance enhancements are commonly undertaken with respect to buildings that do not comply with new regulations. Such seismic strengthening has already been completed in 95.6% of the public elementary and junior high school buildings (as of April 1, 2015) in the country. However, some of office buildings are difficult to be retrofitted, mainly, because their services should not be disrupted. For that reason, external retrofitting has become a common method for improving the seismic performance of such buildings, and, a manual, which focuses on external seismic retrofitting for existing Reinforced Concrete (RC) buildings, is published (JBDPA, 2002). As various reinforcement design methods and structural provisions are described in this guideline, they have been used ~~in~~ by many structural designers in Japan. Understandably, external retrofitting, like bracings, affects greatly the external appearance of buildings and does not allow a comfortable view from the window. Enhancing the seismic performance, while maintaining the external appearance, is generally possible with outer wall frame reinforcements in RC structures. However, this technique increases the external dimension and puts additional load on existing frames, and there is a possibility that the effect on the foundation cannot be ignored. With respect to cost, a large investment is needed with the current labor force shortage in Japan. In contrast, the external design and appearance are greatly altered if strengthening by steel braces is employed giving priority to economic considerations. Based on the aforementioned reasons, developing innovative seismic retrofitting technique is necessary. In this regard, a method called the “Steel Ivy seismic retrofit technique,” which is labor-saving at a construction site and minimizes extra loading on the existing frames with due consideration to the external design was developed and successfully used in building strengthening.

1.2 Concept of “ Steel Ivy seismic retrofit technique ”

Fig. 1.1 depicts the “Steel Ivy seismic retrofit technique.” In this technique, corrugated steel plates are used to enhance the seismic strength. The corrugated steel plate walls (Y.Ohta et al. 2006) are used in rectangular prefabricated units that can be externally attached to existing frames to increase their seismic capacity.

The location and size of the corrugated steel plate walls are aligned with the existing window openings, thereby creating a steel frame that does not significantly alter the view from the window. With respect to shear deformation in the corrugated steel plate walls, the shear buckling length is shortened because each folded steel plate bears its own share of the shear force. This shortening increases the shear buckling strength compared to that of flat steel plates. Moreover, very little stresses are generated because of axial and bending deformations along the axis of the corrugated steel plate walls since they expand and contract along their axis similar to an accordion. This movement makes it possible to use thinner steel plates to make the reinforcement frame lighter.

The rectangular steel frames are only connected to the beams of the existing structure and not to the columns. This setup enables the stress generated from the seismic load on the corrugated steel walls to be transferred to the existing structure through the beam connections. As this technique minimizes the extent of existing tile removal with no dependency on the existing column, it makes it highly flexible in the reinforcement layout design.



① After removing tiles of existing beam side, and setting anchors

②Setting Rectangular steel frame

③Filling Non-shrinkage grout into the joint

Fig. 1.1 – Outline of “Steel Ivy seismic retrofit technique”

Stresses are generated in the connections between the existing beams and reinforcement frames due to the forces developed during earthquakes as shown in Fig. 1.2. These connections are designed considering the bending moment and shear force resulting from such load conditions. Fig. 1.3 depicts the connection details with the existing beams. The anchors set on the existing beams and headed studs welded on the reinforcement frame side are jointed by pouring a non-shrinkage grout in the space between the existing beam and the reinforcement frame. This method of post-installed anchors is presented in Ref. (3), where the shear capacity of a single bonded anchor is expressed by equations (1)~(3) and shear strength contribution of each stud is expressed by equation (4). The former equations are based on the experimental studies in Ref. (5) and Ref. (6), and the latter one is based on the experimental studies in Ref. (7), Ref. (8), Ref. (9) and Ref. (10). Reduction coefficient in Eq. (1) aims to restrain seismic shearing deformation to less than 2mm . In " Steel Ivy seismic retrofit technique ", the resisting mechanism is divided into three assumed components, one related to bending moment (M_{in}), another one related to shear force (Q) and the other related to eccentric moment (M_{out}). Their design is independently carried out for each of them.

・Shear capacity Q_a of a single bonded anchor

$$Q_a = \phi_s \bullet \min[Q_{a1}, Q_{a2}] \tag{1}$$

$$Q_{a1} = 0.7 \bullet {}_s a_e \bullet \sigma_y \tag{2}$$

$$Q_{a2} = 0.4 \bullet \sqrt{E_c \bullet \sigma_B} \bullet {}_s a_e \tag{3}$$

where: ϕ_s : Reduction coefficient ,0.7

σ_y : Specified yield strength of steel anchor (N/mm^2)

${}_s a_e$: Cross section area of anchorage anchor (mm^2)

σ_B : Compressive strength of concrete of existing beam (N/mm^2)

E_c : Young's modulus of concrete calculated based on σ_B (N/mm^2)

・Shear strength q_{ds} contribution of each stud

$$q_{ds} = 0.64 \bullet \sigma_{\max} \bullet a_s \tag{4}$$

where: $\sigma_{\max}$: Tensile strength of stud (N/mm^2)

a_s : Cross section area of stud (mm^2)

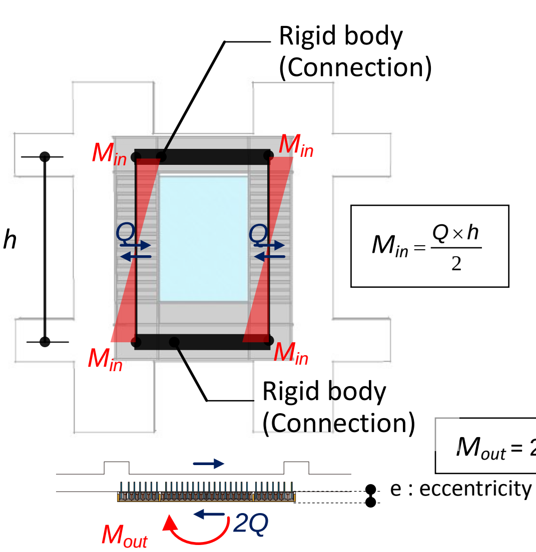


Fig. 1.2 – Forces on steel frame

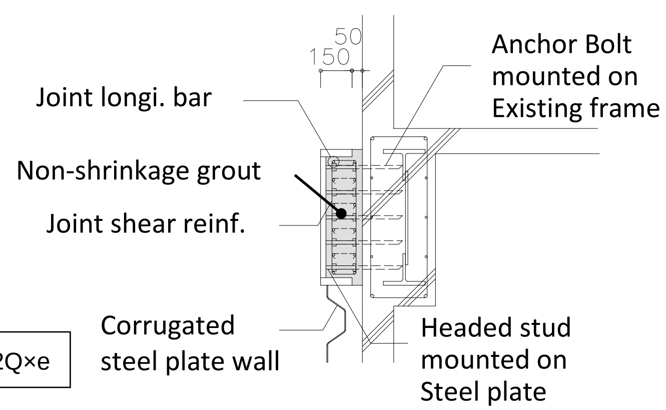


Fig. 1.3 – Detail of rigid joint

The bending moment is resisted by the corrugated plate and consequently by only the connection parts located at the upper and lower parts of the corrugated plate, as descriptively shown in Fig. 1.4. The shear force is resisted by the remained connection part. Therefore, as the eccentric moment is generally small, the calculated resistance is considered negligible in comparison to the two other components.

Confirming the structural safety through experimental tests is necessary because the current technique is novel and not already mentioned in the current design codes. The experiments are conducted to ascertain whether the connection between the existing beam and the reinforcement frame could function as a rigid body and whether the reinforcement frame could exhibit the desired strength at the targeted deformation performance.

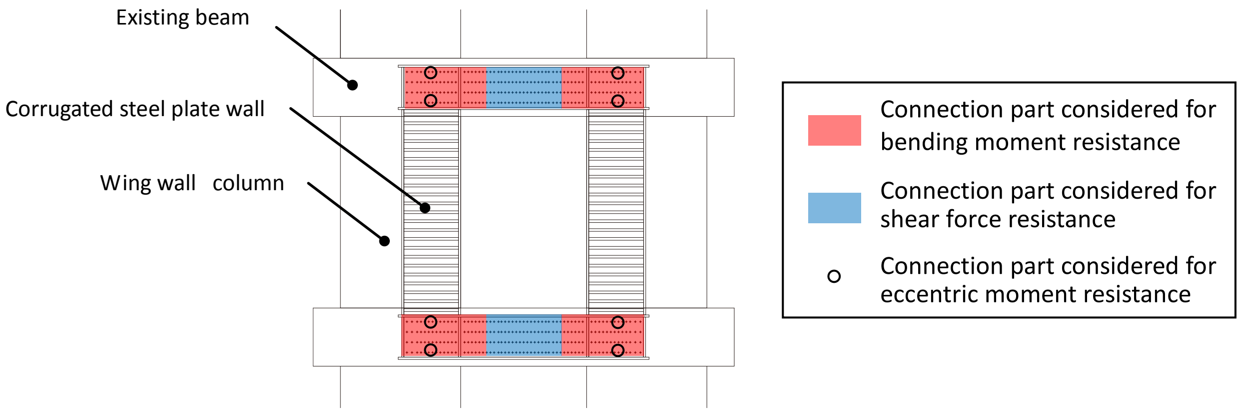


Fig. 1.4 – Connection parts and assumed resistance distribution

2. Experimental Study

2.1 Experimental purposes

Applying the proposed method in an actual building reinforcement was already planned before the experiments were performed. Therefore, simulating a part of the actual building location to be reinforced was necessary in planning the experiments. Section 3 describes the actual building overview. This method can also be applied in reinforcing existing RC structures, although the existing frame in the experiments was made of the Steel-Reinforced Concrete (SRC).

The two main purposes of the experiments were as follows:

1) ascertain the structural performance of the rigid connection to the reinforcement frame, and

2) ascertain the structural performance of the combination of the existing frames and the reinforcement frame.

2.2 Detail of specimen and test setup

Fig. 2.1 shows the specimen shape and dimensions. Table 2.1 describes the properties of the materials used. Using a single half-scale model specimen to simulate a one-story, one-span SRC frame of the actual building, reinforcement was undertaken by applying the “Steel Ivy seismic retrofit technique”. The columns with wing walls that would have a shear failure mode were adopted based on the actual detailing of the columns in the SRC frame. Fig. 2.2 shows the loading setup and measurement points. The total of the vertical axial forces on the left and right sides was kept constant during test. The horizontal force was applied on the specimen using the upper two horizontal hydraulic jacks according to the reversed cyclic loading pattern shown in Fig. 2.3. The lower two horizontal jacks were placed to control the horizontal displacement at the lower part as zero. The horizontal drift angle R used in the displacement control was calculated by dividing the horizontal displacement δ (i.e., mean of δ_1 and δ_2) at the load applied point by the story height h. The horizontal force was applied at the horizontal drift angles of R = 0.25, 0.5, 1.0, 2.5, 5.0, 7.5, 10, 15, 20 × 10^{-3} rad. The last angle was +30 × 10^{-3} rad. One cycle each of the loading was tested for the smaller drift angles of R = 0.25 and 0.5 × 10^{-3} rad. Two cycles each of the loading were tested for the other horizontal drift angles.

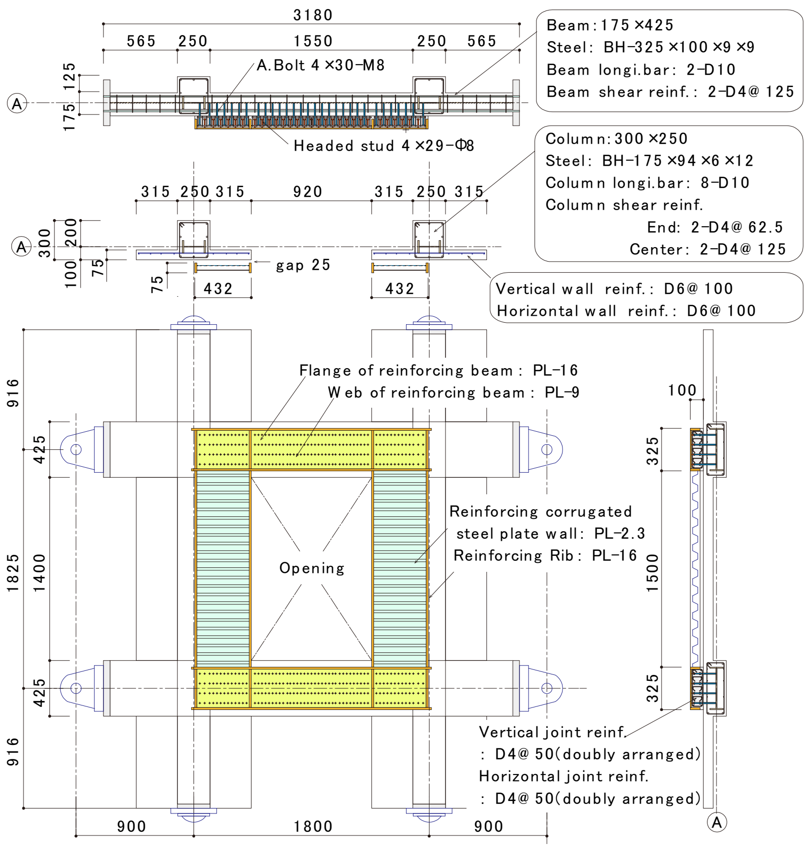


Fig. 2.1 – Detail of specimen (Unit: mm)

Table 2.1 – Mechanical properties of concrete and steel

☐Concrete

Material	Part	Compressive strength [N/mm^2]	Splitting tensile strength [N/mm^2]	Modulus of elasticity [N/mm^2]
Concrete using lightweight aggregate	Existing SRC frame	29.8	1.81	17000
Non-shrinkage grout	Connection	56.8	2.70	21700

☐Steel

Material	Part		Yield strength [N/mm^2]	tensile strength [N/mm^2]
D10	Existing SRC frame	Longitudinal bars	376	536
D6		Wall reinforcement	352	529
D4		Column shear reinforcement Beam shear reinforcement Connection	344	518
PL-12		Column	291	430
PL-9		Beam	295	458
PL-6		Column	286	451
M8	Retrofit frame	Connection (A.Bolt)	557	792
ϕ 8		Connection (Headed stud)	428	463
PL-16		Flanges of reinforcing beam Reinforcing ribs	260	419
PL-9		Web of reinforcing beam	295	458
PL-2.3		Corrugated steel plate wall	420	569

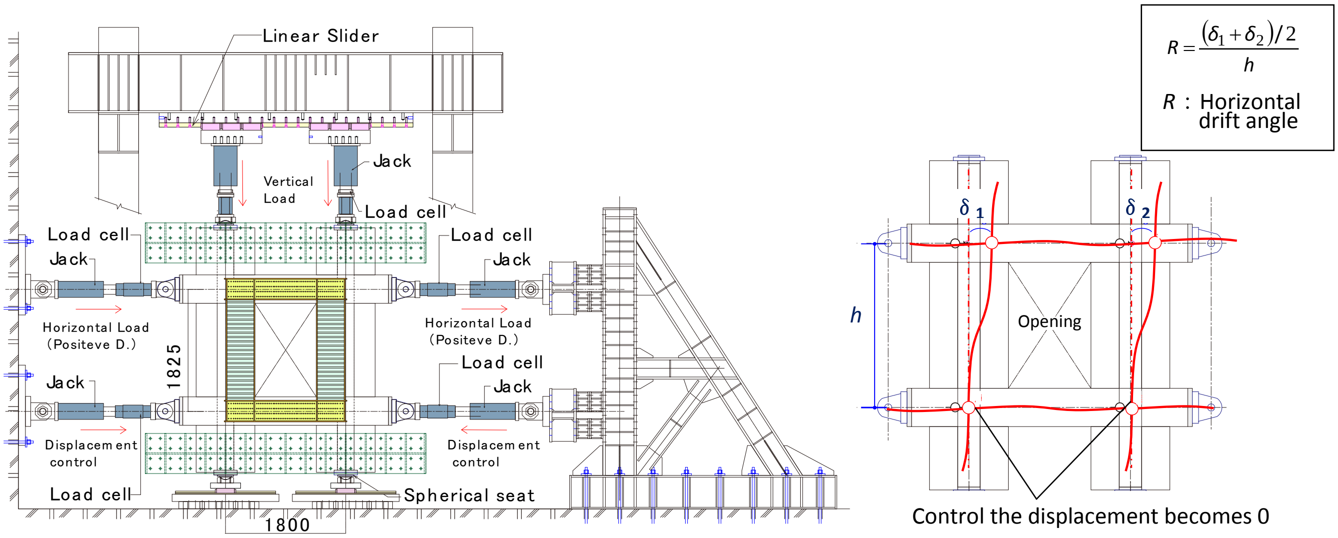


Fig. 2.2 – Test setup and Measurement points

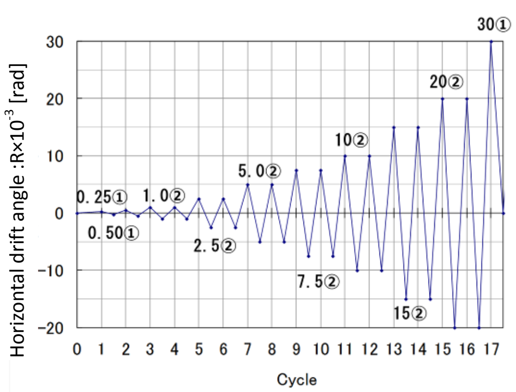


Fig. 2.3 – Cyclic loading pattern

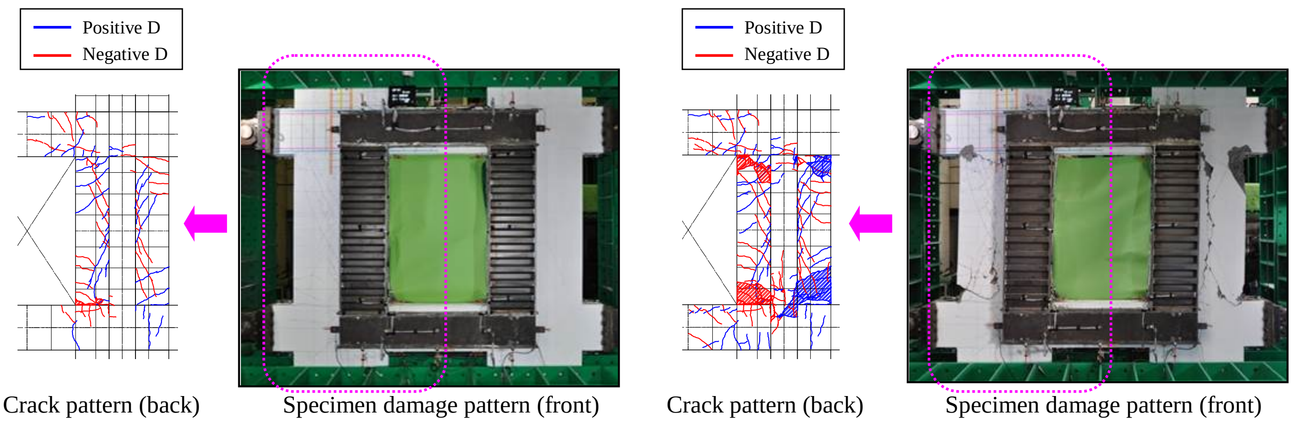
2.3 Results of experiment

Fig. 2.4 shows the specimen's damage state on its front and back sides at the horizontal drift angles of 7.5 × 10^{-3} rad and 20 × 10^{-3} rad. Fig. 2.5 illustrates the relationship between the horizontal force and the horizontal drift angle. Fig. 2.6 shows the relationship between the strain of the corrugated steel plate wall and the horizontal drift angle. This strain was measured using triaxial strain gauges placed at the center of the wall web zone. The figure shows that the corrugated steel plate wall experienced yielding.

The SRC frame's flexural cracks appeared in the wing wall of the specimen and the beam at R = 2.5 × 10^{-3} rad. Furthermore, shear cracks appeared on the wing wall at R = 3.5 × 10^{-3} rad. Meanwhile, the bending failure of the wing wall occurred at R = 7.5 × 10^{-3}rad. The frame strength started to drop within the same cycle, thereafter, because the shear cracks on the wing wall penetrating the column surface occurred at R = 10 × 10^{-3} rad. No other significant failure was observed up to the end of loading, although cracks were observed in the mortar of the connection at and over R = 5.0 × 10^{-3} rad.

Besides the experimental results, Fig. 2.5 shows the calculated shear strength of the strengthened SRC frame which is obtained by summing up the yield strength of the corrugated steel plate walls and the shear strength of the existing columns with wing walls. The calculations for the columns with wing walls were based on the method described in Ref. (2). The calculations for the corrugated steel plate walls were based on Table 2.3 presents a comparison of the test and theoretical strengths relative to each part. These results suggest that the strength of the entire frame can be evaluated from the cumulative strength of the existing frame and corrugated steel plate walls.

However, it should be noted that the stiffness of the reinforcing frame varies if the height or length of the corrugated steel plate walls changes. The in-plane relative displacement at the connection was less than or equal to 1 mm, which was exhibited when the maximum reinforcement strength was reached at R = 10× 10^{-3} rad. This value is less than the allowable limit (2mm) of shearing deformation described in Ref (3). This result demonstrated the integrated behavior of the reinforcement because the in-plane relative displacement at the connection at the ultimate story deformation angle was only 2 mm.



(a) R=7.5/1000 rad (b) R=20/1000 rad

Fig. 2.4 – Damage state of specimen

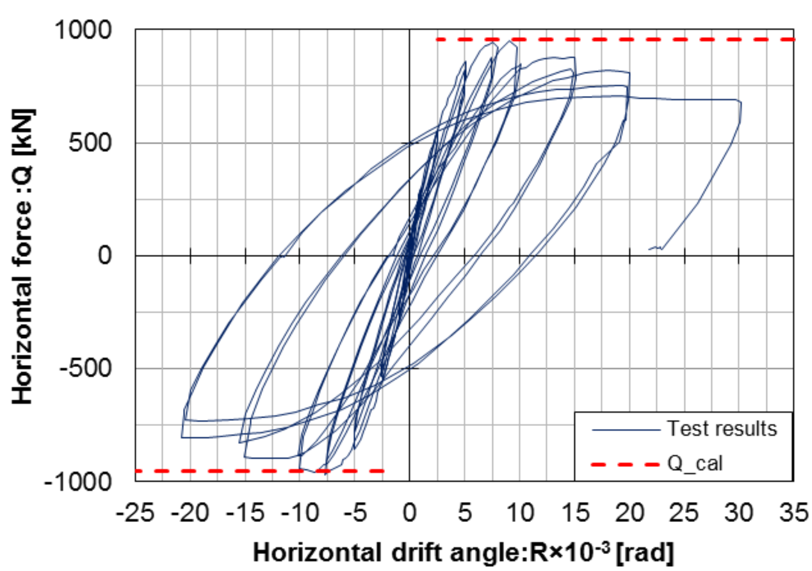
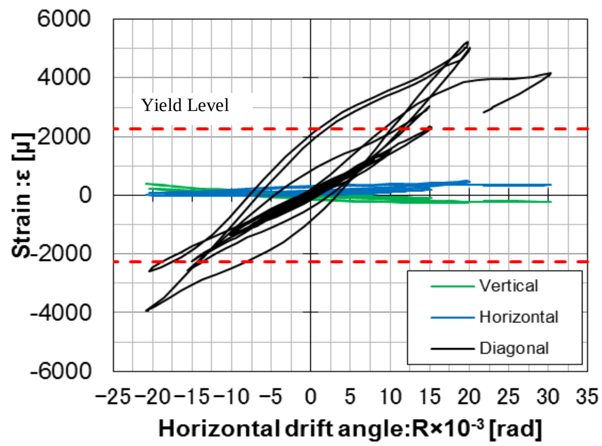


Fig. 2.5 – Test result (Entire frame)

Table 2.3 – Comparison of test results with calculated values

	Entire frame	Corrugated steel plate walls	Existing SRC frame
Experimental value Q_{exp} [kN]	952	—	—
Calculated value Q_{cal} [kN]	955	446	509
Q_{exp} ⁄ Q_{cal}	1.00	—	—



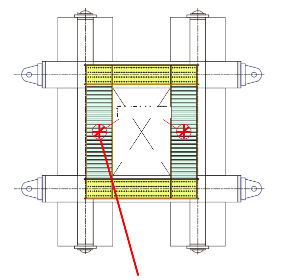


Fig. 2.6 – Test result (Left side of Corrugated steel plate walls)

3. Application Example

3.1 Project overview

Table 3.1 shows the project overview. The building is the headquarters of KOKUYO Co. Ltd., which is a company with global business operations in manufacturing and sales of stationery, office furnitures, and business equipments. The current headquarters building was constructed in 1969. An extension building based on the new seismic design regulations was constructed and connected to the old building using an expansion joint later in 1984. The building was still used as the headquarters and preferred by employees, although 47 years have passed since the building was completed.

Table 3.1 – Project overview

Name of building：Headquarters of KOKUYO Co. Ltd.	Covered area：1082.64 ㎡
Location　：Osaka City, Osaka, Japan	Total floor area：8803.20 ㎡
Design and construction：Takenaka Corporation	Height：30.85m
Structure：SRC	Number of stories：8
Structure type： Frame structure with shear walls	Constrution time：1969
Concrete strength：Fc21（lightweight aggregate）	（Additional building：1984）
Foundation type：pile foundation	Seismic retrofitting time：2014

3.2 Concept of seismic retrofitting and Structural planning

The owners' requests were "producing an outside appearance suitable for a global company with slight changes to the existing facade", "using the building during strengthening" and "improving the office environment". A new external reinforcement technique called the "Steel Ivy seismic retrofit technique" was developed and applied to the building to satisfy these requirements. As indicated in the name given to this technique, the design concept involved covering some parts of the building exterior with steel plates, as the covering of an ivy, to firmly reinforce the building. Fig. 3.1 shows the facade before and after the renovation.

Based on the seismic evaluation according to the method described in Ref. (2), the building in the east–west direction for the first six floors and in the north–south direction for the first five floors did not have the requisite seismic performance. Fig. 3.2 shows the retrofitting layout. The exterior walls on three sides of the building were reinforced with the "Steel Ivy seismic retrofit technique" to retrofit the building. The south side, where the old building was connected with the additional building, reinforced with steel braces because it was an internal space. The first floor on the north–south side was strengthened using RC shear walls to compensate for the axial strength deficiency of the columns.

(a) before (b) after
Fig. 3.1 – Exterior design

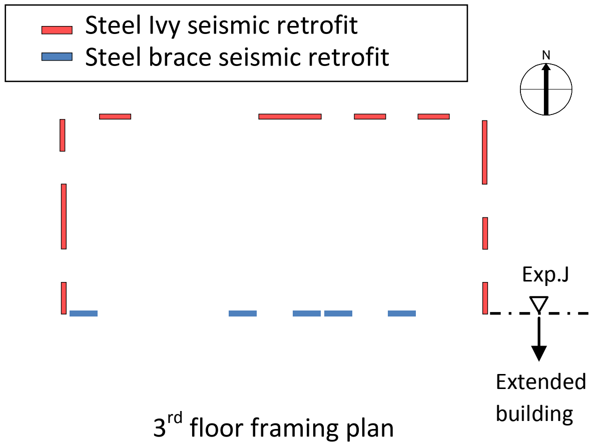


Fig. 3.2 – Layout of retrofitting

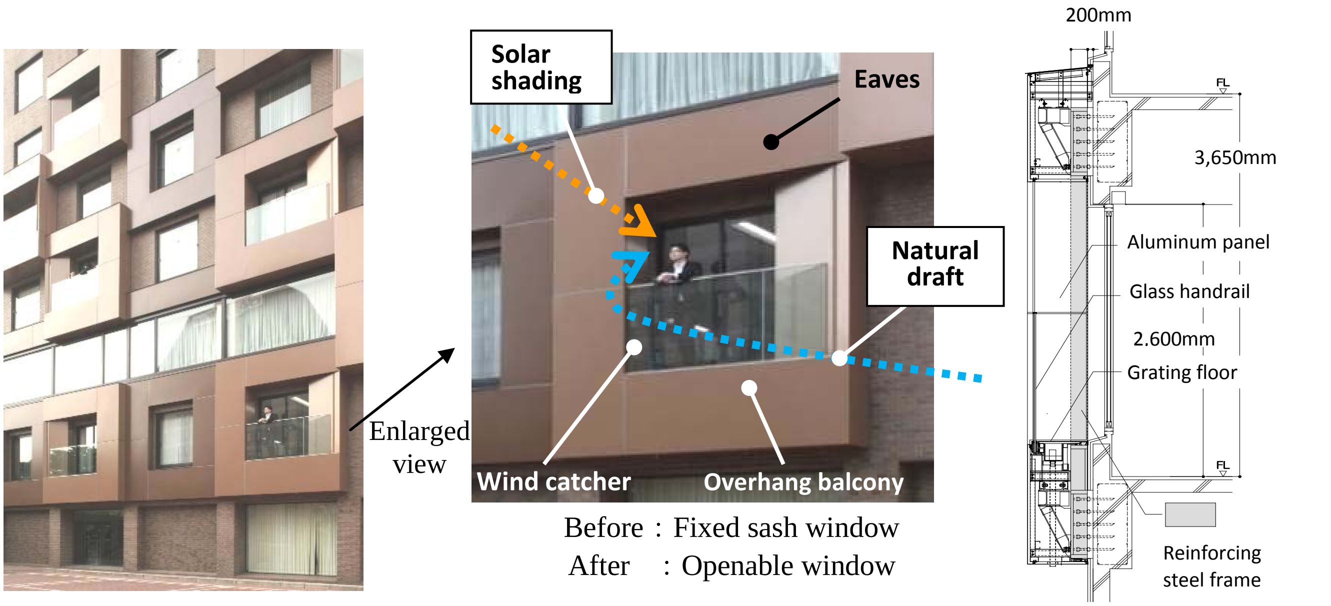
3.3 Characteristic of architectural design

(1) Vitalized exterior design

This technique enables the construction of retrofit elements at 200 mm from the external wall. Therefore, the outer dimension of the exterior panels was varied in each unit in three stages to create a vitalized exterior design utilizing 3D unevenness. Moreover, color shades for the exterior panel were chosen considering the color harmony with the existing tiles. A unique exterior design was then created while the orderly appearance of the existing design was retained.

(2) Improving the working environments

Overhang balconies were constructed on the retrofitting frame to improve the working environment. The existing fixed windows were also changed to openable ones, thereby enabling free access and natural ventilation. The technique was successful in enhancing the attraction of the building by adjusting the outer dimension of the exterior panels covering the reinforcement frame, which can provide solar shading and allow natural drafts as energy saving measures. Fig. 3.4 depicts the concept.



(a) Outside appearance (b) Design for Environment (c) Sectional detail drawing
Fig. 3.4 – Concept of overhang balconies

4. Conclusion

Test was conducted on a specimen representing a reinforced structure in an existing SRC building retrofitted using the proposed "Steel Ivy seismic retrofit technique." Accordingly, the shear in the proposed connection can be greatly minimized, thereby improving the integration of the existing structures with the reinforcement frames, if the mechanical anchors and headed studs were appropriately designed based on Ref. (3). Moreover, the seismic performance of the combined structure after retrofitting can be evaluated in term of the lateral capacity (Q_t), as given in equation(5), by cumulating the strengths of the existing structure and the reinforcement frames, within the proportions' limits of this experiment. Shear capacity of the reinforcement frames (Q_r) is obtained by equation (6), while that of the existing structure (Q_e) shall be calculated according to the guidelines of Ref. (1) or Ref. (2).

$$Q_t = Q_r + Q_e \tag{5}$$

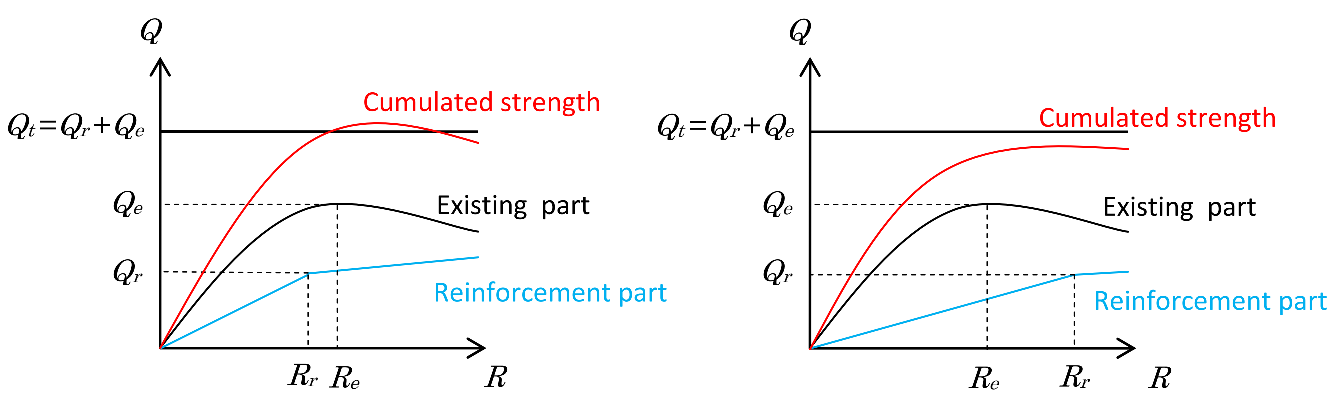
$$Q_r = 2 \bullet t \bullet L \bullet f_y \tag{6}$$

where: t : Steel plate thickness (mm)

L : Steel plate length (mm)

f_y : Specified yield strength of steel plate (N/mm^2)

In order to expand the application of the proposed strengthening method to various types of buildings and evaluate properly the strength of the retrofitted structures, it is important to evaluate appropriately the stiffness of the reinforcement frames. If the stiffness of the reinforcement frames is extremely lower than that of the existing part, as shown in Fig. 4.1, cumulation of strengths would not be appropriate because the strength degradation of the existing part, occurs before the maximum strength of the reinforcement part is reached. The stiffness evaluation of "Steel Ivy seismic retrofit technique" is an issue that will be dealt with in a future study.



(a) Comparable stiffness case (suitable) (b) Lower stiffness case (not suitable)

Fig. 4.1 –Appropriate stiffness and cumulative strengths

The proposed "Steel Ivy seismic retrofit technique" was applied to the "KOKUYO Headquarters Building." The authors succeeded in elegantly retrofitting the building using a new exterior design that retained the orderly appearance of the existing design. Moreover, they created an added value by improving the working environment using the reinforcement frames for overhang balconies and solar shades.

The proposed seismic retrofitting technique was useful in improving all aspects of "strength/utilization/elegance" of the existing buildings. Improving the seismic strength was the most important for the buildings that do not comply with new regulations. However, it is also important to provide additional benefits to the owners, such as vitalizing exterior designs and improving the working environment for acceleration of their reinforcement. The authors believe that the building used here was a good case study.

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