SEISMIC RETROFIT OF RC BUILDINGS WITH PRESTRESSED PRECAST CFT AND FRC BRACES

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ABSTRACT :

This research aims to propose a simple seismic strengthening method which satisfies short construction period and low construction cost by using no rebar or bolt anchorage. A prestressed precast concrete brace system was proposed by the authors in 2001 and this study introduces a revised brace system using concrete filled tube and precast fiber reinforced concrete to enhance its deformation capability and aesthetics. Two half scale portal frames were constructed based on the old Japanese building standard and strengthened with two kinds of brace system without using rebar nor bolt anchorage; one made of precast fiber reinforced concrete and the other made of concrete filled tube. Each brace was a single line element and easily placed in a existing frame. Braced frames showed more than 70% increase in shear capacity and enhancement in ductility. It was also shown that the existing design equations for axial strength of a brace, shear strength of column-beam joint, and bearing strength can be applied to design the proposed brace system.

KEYWORDS: Seismic retrofit: Prestressed CFT brace: Prestressed Precast FRC brace: Strengthening

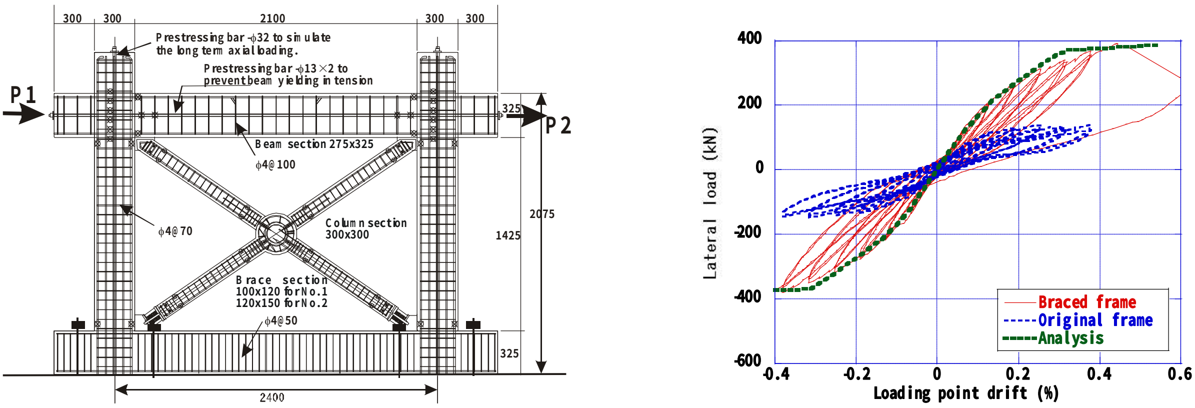
1. INTRODUCTION

After major earthquakes such as the Northridge and Kobe earthquakes in 1990's, the seismic upgrading of existing buildings has been attracting more attention than ever. Upgrading of seismic performance of buildings can be achieved by increasing strength or ductility. However, many existing buildings in Japan have not had seismic upgrading since construction is costly due to intensive labor work and long suspension of service. This research aims to develop a simple seismic strengthening method which satisfies short construction period and low construction cost by not using rebar or bolt anchorage. For this purpose, an X-shaped precast prestressed concrete brace system was developed in 2001 at Kyoto University [1]. In this report, a revised brace system made of concrete filled tube and fiber reinforced concrete is introduced for better aesthetics and deformation capability.

The previously proposed X-shape precast prestressed concrete brace consisted of four precast units as shown in Fig. 1(a). They were assembled at construction site and prestressing force was introduced to two lower legs. Gaps between brace ends and frame corners were filled with high strength no-shrinkage mortar. After hardening of mortar, the prestressing force was released. Then the X-shape brace extended by itself and was fixed to a boundary frame. When a frame with an X-shape brace is subjected to lateral seismic load, only one of diagonal members basically works effectively in compression. However, the remaining diagonal member is free to move because concrete does not carry tension force, and the tensile diagonal member comes off from the surrounding frame. To avoid this, a special device with a flat spring and steel pipe (FSSP) in Fig. 2 (c) is installed at the bottom end of each diagonal member. This device makes possible to maintain a certain amount of compressive force in the diagonal member even if the brace experiences elongation under reversal seismic force. Fig. 1(b) shows the lateral load – drift relations of the braced frame and the original unbraced frame. It can be seen that the lateral load capacity of the braced frame was three times as high as that of the original unbraced frame. Since the peak load was determined by the compressive strength of the brace, the postpeak behavior was brittle and the load dropped suddenly. Because of this brittle failure mode, the required lateral load carrying capacity in design needs to be set higher than that of the ductile frame.

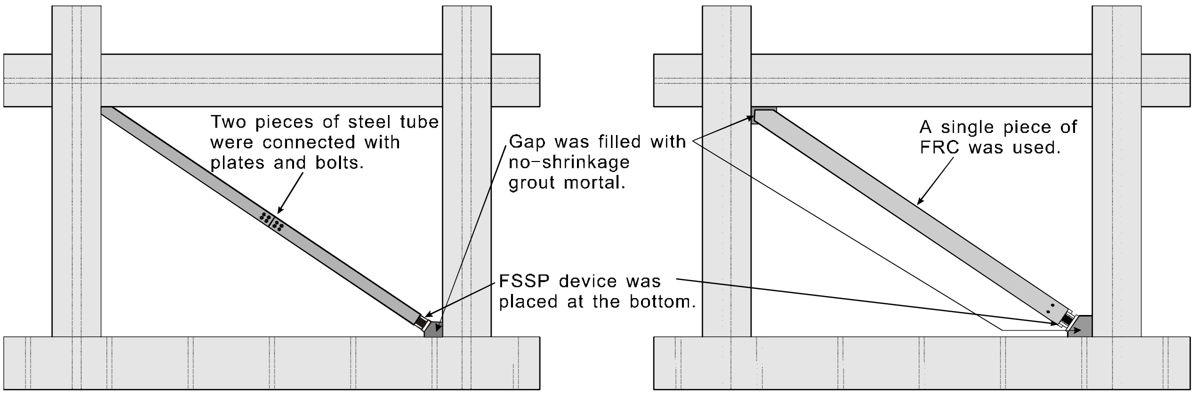
In this paper, a new precast brace is proposed as shown in Fig. 2. Materials of the brace were either concrete filled tube (CFT) or fiber reinforced concrete (FRC) to increase the deformation capability so that the required lateral load carrying capacity in design can be decreased. The configuration was changed to a single diagonal line element instead of X-shape so that the brace aesthetically looks better and an opening can be made if necessary. Since a single diagonal brace can resist against force in one direction but does not work in opposite direction, it may be necessary to place brace for the opposite direction at some other spans. However, placing simple line elements instead of X-shape elements saves construction time and labor. Using CFT has some more advantage in construction. The steel tube of CFT may be divided into several pieces, brought to the construction site using existing elevators, assembled at site, and placed in the existing frame. The inside of the steel tube is filled with grout mortar after the steel tube is placed in the frame. In this way, CFT necessitates the minimum amount of construction materials and excludes heavy construction equipment.

In 2001, prestressing force was applied with prestressing rods embedded in the X-shape assemblage. Since the one end of the rod was anchored at the central hollow circle in Fig. 1(a), the introducing process of prestressing force was not very efficient and it was impossible to take out prestressing rods after the construction. In a new system, the prestressing force is applied to the whole length of the brace with external rods. Rods can be reused and the brace can be taken out by reapplying the prestressing force if necessary.

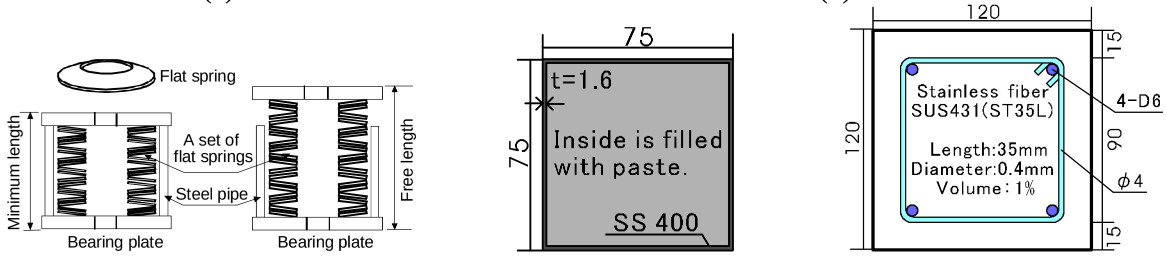


(a) Specimen configuration (Unit: mm) (b) Load-drift angle relation

Fig. 1. The first generation bracing system and lateral load – displacement relation [1]



(a) CFT01 (b) FRC01



(c) Flat spring and steel pipe (FSSP) (d) CFT01 brace (e) FRC01 brace

Fig. 2. Specimen configurations

2. TEST SETUP

Two half-scale specimens (CFT-S60 and FRC-L30) were constructed with different brace materials as shown in Fig. 2. The surrounding reinforced concrete portal frames, as shown in Fig. 3, were identical and were assumed to be the sub-assemblage of a four-story reinforced concrete building, which was designed following the old Japanese Building Standard [2]. The brace of CFT-S60 was made of concrete filled tubes and that of FRC-L30 was made of fiber reinforced concrete. Each brace was installed in the reinforced concrete portal frame with a FSSP (flat spring and steel pipe in Fig. 2(a)) device so that the brace would not come out of the portal frame when experiencing elongation. If the FSSP device is compressed by more than 32kN, the spring contracts inside the steel pipe and the steel pipe practically carries the whole axial load. Mechanical properties of materials are shown in Table 1.
Before applying the horizontal load, prestressing force of 450kN ($0.28f'_cbD$) and 324kN ($0.20f'_cbD$) was applied to the beam and each column, respectively, with internal unbonded prestressing steel bars. The column axial force corresponds to the axial force of the first story column due to the gravity load. Beams were prestressed to avoid the tension failure.

The lateral load carrying capacity of the reinforced concrete portal frame without the brace was 212kN. By installing the brace, braced specimens were designed to have lateral load capacity of 335kN for CFT and 585kN for FRC at which the brace was to buckle. Against this ultimate stage, the shear capacities of the beam, the columns, and column-beam joints were computed as Table 2 to make sure those component do not fail. Each component had the capacity larger than the required shear force. The table also shows prestressing force of the brace. The lateral loads with equal magnitude were applied at either end of the beam controlling the drift angle as shown in Fig. 4. Enforced positive displacements were five times as large as negative displacements so that the surrounding reinforced concrete portal frame does not suffer too much damage in the negative loading.

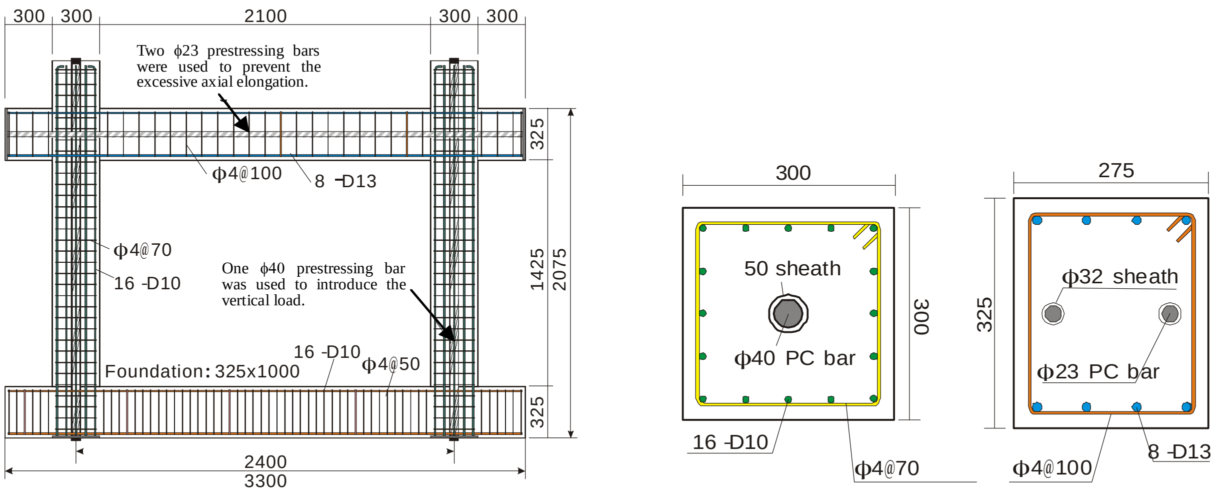


Fig. 3. Reinforcing bar arrangement of the portal frame

Table 1. Mechanical properties of materials

(a) Concrete

Specimen	Member	Compressive strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)
CFT-S60	Frame	29.6	2.91	25.1
	* Brace	62.7	4.04	20.8
FRC-L30	Frame	31.8	26.4	2.89
	Brace	30.1	22.2	3.31

* Properties of the grouting mortar in steel tube.

(b) Steel

Type	Yield strength (MPa)	Tensile strength (MPa)	Young's modulus (GPa)
D13	358	512	181
D10	371	527	179
D6	415	531	179
ϕ4	522	579	202
CFT tube	338	448	221

Table 2. Shear strengths of members and prestressing forces introduced to the brace

Specimen	Component	Shear capacity Qu*1	Design shear force when the brace buckles, Qr (kN)	Qu/Qr	Prestressing force of brace (kN)
CFT-S60	Column	86.6	49.0	1.8	42.1
	Beam	67.7	36.3	1.9	
	Joint*2	444	182	2.4	
FRC-L30	Column	86.6	34.6	2.5	32.9
	Beam	67.7	21.6	3.1	
	Joint*2	444	157	2.8	

*1: Capacity was computed based on Ref. [3].
*2: Joint stands for the column-beam joint.

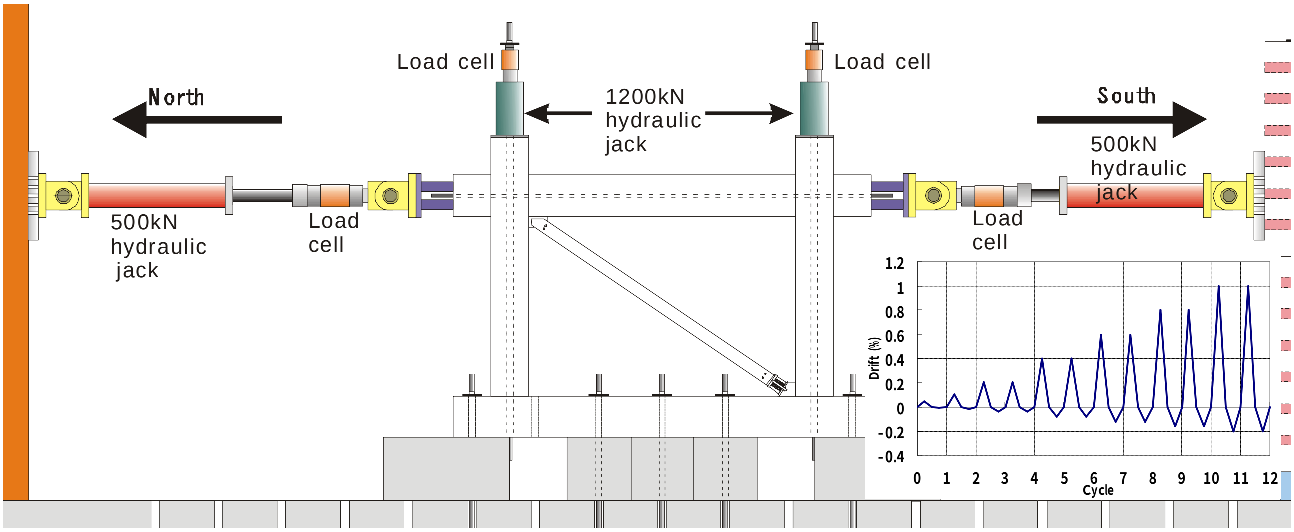


Fig. 4. Loading system and loading protocol

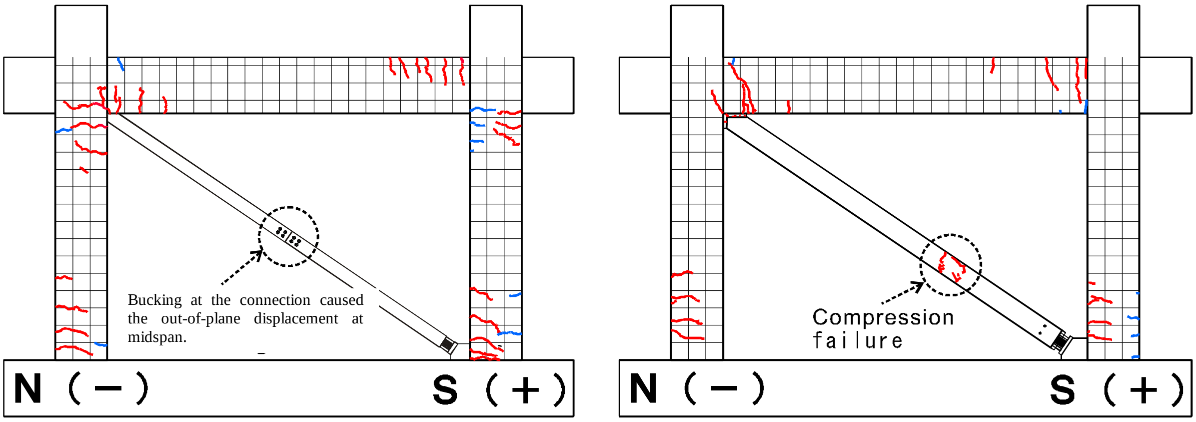
3. TEST RESULTS

The observed damage of two specimens at drift angle R=0.8% is shown in Fig. 5. The portal frame had some minor flexural cracks in both specimens. CFT-S60 failed due to buckling of the brace, and FRC-L30 failed due to compression failure of the brace. Load – drift angle relations are shown in Fig. 6. A solid line represents the total load and a lightly shaded line represents the shear force carried by two columns. The shear force carried by columns were obtained by subtracting lateral load contribution of the brace from the total lateral load. Lateral load contribution of the brace was the horizontal component of the axial force which is computed in Fig. 7. Axial force was computed from strain gages on four faces of the brace and stress-strain relations obtained from the material test. Both braces showed a relatively stable and ductile behavior.

In CFT-S60, the initial stiffness changed when cracking was observed at the north column-beam joint and the beam ends at R=0.2%. The load carrying capacity still increased until the yielding of the beam at R=0.6%. The number of cracks increased from R=0.4% at the column-beam joint but the maximum crack width was less than 0.1 mm. The axial force of the brace reached the maximum value at R=0.4% and the buckling started resulting in the second stiffness change. Total lateral load reached the peak at R=0.6% when buckling deformation of the brace was visually observed. Load carrying capacity decreased gradually after buckling but brittle failure mode was not observed.

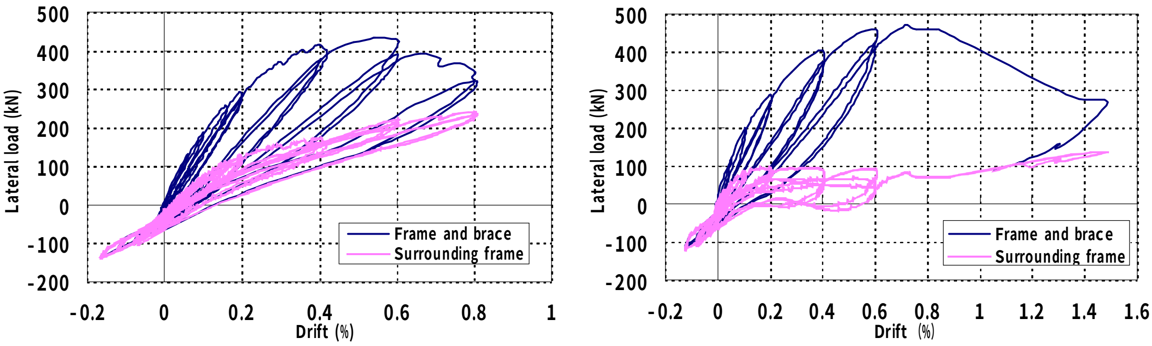
In FRC-L30, the reinforced concrete frame showed the first cracks at the north end of the beam at R=0.1%. The number of cracks increased at R=0.4%, and longitudinal bars of brace yielded in compression but buckling was not observed. The load carrying capacity increased up to R=0.7%, and the compression failure occurred at the brace at

R=0.8%. Although two specimens failed due to buckling or compression failure, lateral load – drift angle relations showed stable and slow post-peak degradation.



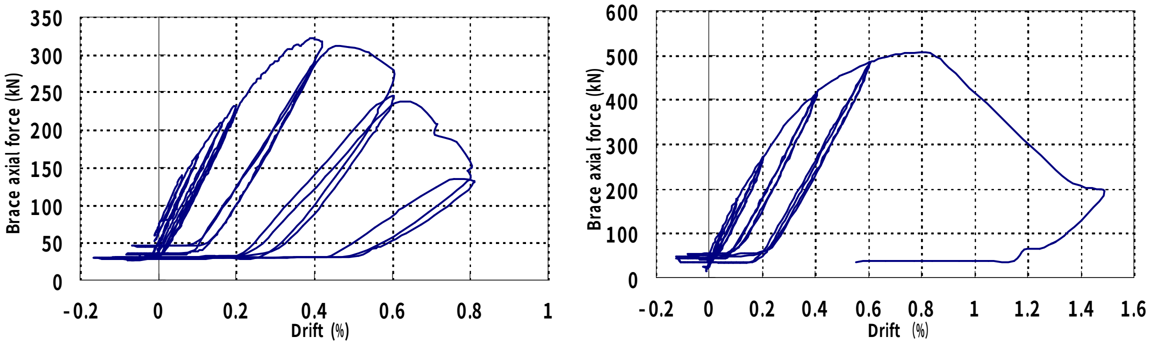
(a) CFT-S60 (b) FRC-L30

Fig. 5. Observed damage at R=0.8%



(a) CFT-S60 (b) FRC-L30

Fig. 6. Load – drift relations



(a) CFT-S60 (b) FRC-L30

Fig. 7. Axial compressive force of the brace – drift relations

4. METHODS TO EVALUATE THE CAPACITIES OF THE BRACED FRAME

4.1. Compressive strength of braces

The compressive strength of FRC braces is computed by considering the initial imperfections in this section based on Ref. [3]. Moment diagram is shown in Fig. 8(a) when the out-of-plane force, $\alpha_1 N$, acts at the midspan and in Fig. 8(b) when the axial force, N, acts with eccentricity, $e(=\beta D)$. Moments at the midspan for each case, ${}_B M$ and ${}_e M$, are expressed as follows, respectively.

$$ {}_{B}M = \alpha_1 N \ell'/4 = \alpha_1 N \gamma \ell/4 \tag{1}$$
$$ {}_{e}M = Ne = \beta DN \tag{2}$$

where $\ell' = \gamma\ell$ is the probable buckling length, ℓ is the clear span of the brace, D is the beam depth. Axial force – moment interaction at the ultimate state of FRC columns is expressed as follows based on Ref. [5].

When $N_{\max} \geq N > 0.4bDf'_c$ is satisfied, moment at compression failure is expressed as follows.

$$ M_u = \left\{0.8a_t\sigma_y D + 0.12bD^2 f'_c\right\}\left(\frac{N_{\max} - N}{N_{\max} - 0.4bDf'_c}\right) \tag{3}$$

where $N_{\max}$ is the ultimate compressive capacity without moment, b is the beam width, f'_c is the compressive strength of concrete, a_t is the section area of the longitudinal reinforcement, and σ_y is the yield strength of the reinforcement. When the brace experiences the out-of-plane force and eccentric axial load at the same time, ${}_{B}M$ and ${}_{e}M$ should satisfy the following equation at failure.

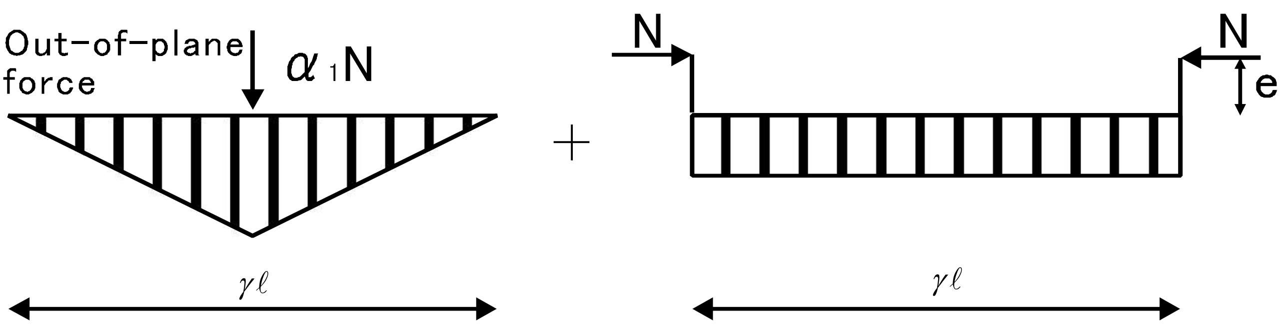
$$ {}_{B}M + {}_{e}M = M_u \tag{4}$$

From Equations (1) through (4), the axial compressive capacity of FRC braces, N_{bu}, is computed as follows.

$$ N_{bu} = \frac{\left\{0.8a_t\sigma_y D + 0.12bD^2 f'_c\right\}\cdot N_{\max}}{\left(N_{\max} - 0.4bDf'_{cc}\right)\left(\beta D + \dfrac{\alpha_1\gamma\ell}{4}\right) + \left\{0.8a_t\sigma_y D + 0.12bD^2 f'_c\right\}} \tag{5}$$

The compressive strength of CFT braces is computed in a similar manner. However, instead of Equation (3), the axial force – moment interaction at the ultimate state of CFT columns was computed based on Ref. [6]. It was combined with Equation (1), (2), and (4) to obtain the axial compressive capacity of CFT, N_{bu}.

Based on the previous experiments, $a_1 = 0.03$, $\beta = 0.0075$, and $\gamma = 0.8$ were used. Coefficient, γ, is multiplied to the clear span of the brace, ℓ, to obtain the probable buckling length, $\gamma\ell$. The probable buckling length was computed considering the end conditions based on Ref. [3]. Computed axial capacity was compared with the test results in Table 3. It can be seen that the equation gives the safer estimate for CFT-S60. The computed estimate is too small for FRC-L30 since the failure was not caused by the buckling but the concentric axial crushing of concrete. Axial force strength for a short column, N_{sc}, was also shown for FRC-L30 in Table 3. N_{sc} is much closer to N_e for FRC-L30 and this supports that the failure mode of the brace was concentric crushing.



(a) Out-of-plane force (b) Eccentric axial force

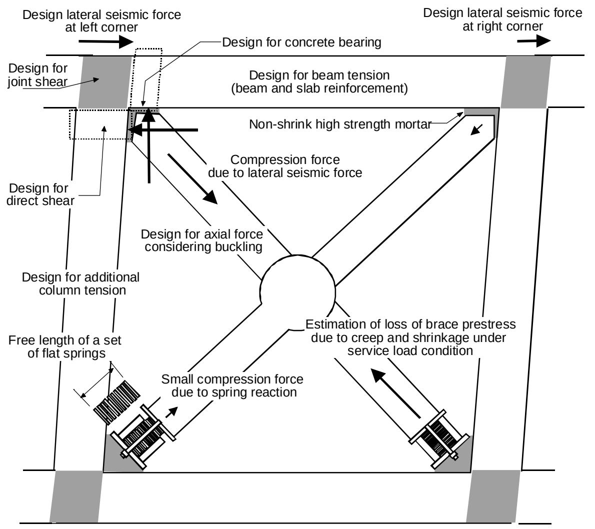
Fig. 8. Suggested load cases to take into account initial imperfections

Table 3. Analytical prediction and test results on the compressive strength

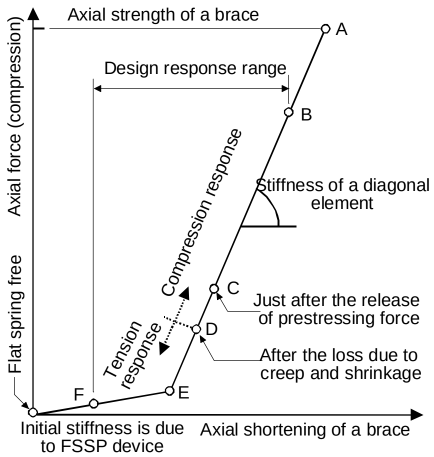
Type	Experiment Ne (kN)	Prediction N_{bu} (kN)	Prediction N_{sc} (kN)	N_e/N_{bu}	N_e/N_{sc}
CFT-S60	321	307	499	1.02	-
FRC-L30	505	255	473	1.98	1.07

DESIGN CONSIDERATIONS

There are several issues to design braced frames in practice and key issues are listed in Fig. 9. It should be noted that the brace enhances strength of the existing frame without decreasing ductility too much. The brittle ultimate failure modes include the buckling of diagonal members, joint shear failure, bearing failure at frame corners, and direct shear failure of beam or column ends. In other cases, ductile failure modes may take place such as axial tensile failure of beams and columns. The design flow is shown in Fig. 10.



(a) Design issues



(b) Force-displacement relation of FSSP

Fig. 9. Major design issues for a proposed bracing system

CONCLUSIONS

The experiment on reinforced concrete portal frame retrofitted with CFT or FRC prestressed brace was carried out and the following conclusions have been drawn.

- It was experimentally shown that the revised prestressed brace system is able to easily retrofit existing reinforced concrete frames with no rebar and bolt anchorage. This leads to short construction period and low construction cost.
- CFT-S60 failed by buckling of the brace but the lateral load – drift relation was relatively ductile until R=0.8%, even after the buckling took place at R=0.4%. The axial force capacity of the CFT brace was computed accurately. The CFT brace is easy to construct and allows the ductile design procedure due to its enhanced ductility.
- In FRC-L30, the grout mortal at the top end of the brace fell off and the bearing region of at the brace failed. The lateral load – drift relation was very ductile in spite of the nature of brittle failure mode. The brace showed better deformation capacity than the originally proposed reinforced concrete brace. By providing proper reinforcement in the grout mortar, the higher lateral load capacity should have been obtained. The lateral load at bearing failure was computed accurately by considering the reduced bearing area.

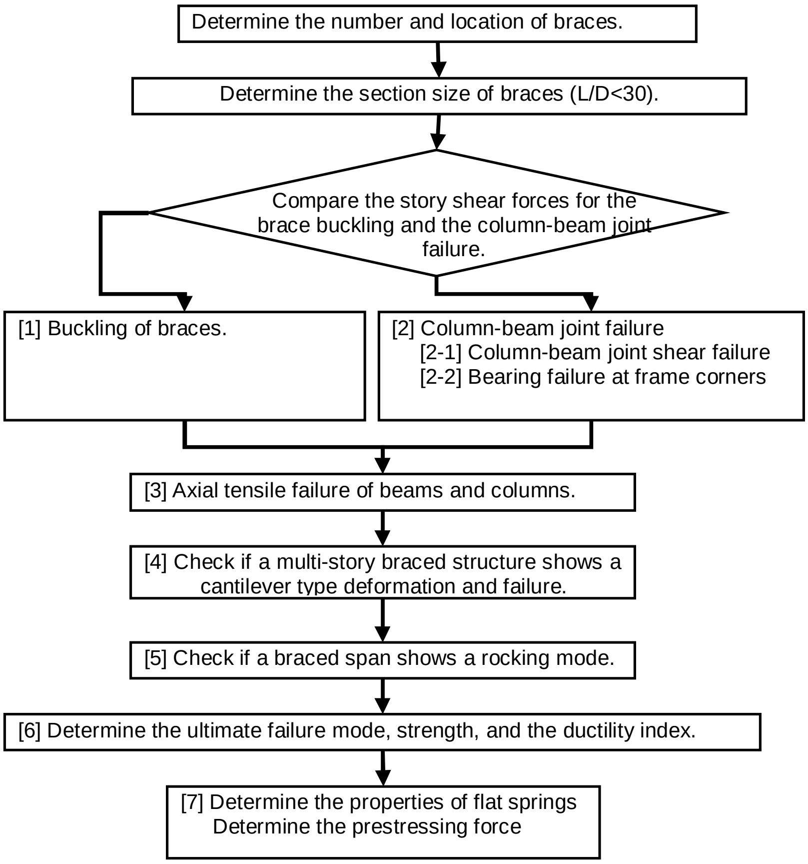


Fig. 10. Design flow of prestressed CFT and FRC braces

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