Seismic Retrofit of Reinforced Concrete Building Structures with Prestressed Braces

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Abstract

A prestressed concrete brace system was first proposed in 2001 to dramatically simplify seismic strengthening procedures. Since the proposed system does not necessitate any steel bar anchorage, the construction period is shorter and the construction cost is lower. The system has been revised in terms of its aesthetics, materials, and construction methods since the first proposal of the system. This paper introduces a series of prestressed concrete brace system and discusses their interesting features. Design procedures and some examples are also introduced with experimental results.

1. Introduction

1.1 Background

After major earthquakes at Northridge (USA), Kobe (Japan), Kocaeli (Turkey), Chichi (Taiwan) in 1990’s, the seismic upgrading of existing buildings has been attracting more attention than ever. At the same period, there was an effort in Japan to address problems related to the seismic rehabilitation of concrete building structures. Based on the efforts, the standard and guidelines for seismic evaluation and retrofit methods were summarized (The Japan Building Disaster Prevention Association, 2005). The efforts have been continuously made and some of them are published in English (Japan Concrete Institute, 2007).

Upgrading of seismic performance of buildings normally be achieved by increasing strength or ductility, or combining both. When a ductility enhancement retrofit method is taken, the construction cost tends to be lower but the response displacement becomes large leading to serious damage of structural components. When a strength enhancement retrofit method is taken, the construction cost is larger but the damage tends to be minor in general. However, many existing buildings in Japan have not had seismic upgrading in any methods since construction is costly due to intensive labor work and long suspension of service. The research project started to develop a simple seismic strengthening system which decreases construction period and construction cost by using no bolt anchorage. Based on this concept, a prestressed precast concrete brace system was initially proposed (Watanabe et al. 2004). The system has been revised since then to refine the configuration, materials and construction procedures. In this paper, a series of prestressed brace system is introduced and their interesting features are discussed with experimental results.

1.2 Basic concept of prestressed brace system

The prestressed brace system resists the external lateral force by placing prestressed diagonal braces in an existing frame as shown in Fig. 1(a). The diagonal members may be made of precast concrete, fiber reinforced concrete, or concrete filled tube. When the diagonal member experiences shortening, the horizontal component of the axial force of the shortened brace resists the external lateral force. When the diagonal member experiences elongation, it is possible to freely come out of the surrounding frame since there is no bolt anchorage. To avoid this phenomenon, a special device with a flat spring and steel pipe (FSSP) in Fig. 1(b) is installed at the bottom end of each diagonal member. FSSP maintains a certain amount of compressive force in the diagonal member even if the diagonal brace elongates.

The axial compression force – shortening relation of a brace is shown in Fig. 1(c). First, the diagonal member and FSSP are assembled and prestressing force is introduced to the assemblage. After placing the assemblage in the frame and releasing the prestressing force, the assemblage comes to Point C. As time goes by, the prestressing force decreased to Point D due to creep and shrinkage of concrete and Point D is considered the condition under the ordinary service condition. The amount of creep and shrinkage is evaluated from empirical equation to evaluate Point D. When the assemblage experiences the seismic force, the brace is designed to move between Point F and Point B so that it does not fail due to excessive shortening and does not come out of the frame under elongation. In this manner, the brace resists the lateral load while it is in the first quadrant of Fig. 1(c). In other words, due to the initial prestressing force, the brace resist the lateral force mainly when it is subjected to compression but to some extent when it is subjected to minor tension as indicated. If it experiences a large amount of tension, the brace no longer carries lateral force. Major design issues related to the prestressed brace system can be seen in Fig. 1(a). These

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Free length of a set of flat springs

Compression force due to lateral seismic force

Small compression force due to spring reaction

Design for joint shear

Design for direct shear

Design for axial force considering buckling

Estimation of loss of brace prestress due to creep and shrinkage under service load condition

Design lateral seismic force at left corner

Design for concrete bearing

Design lateral seismic force at right corner

Non-shrink high strength mortar

Design for beam tension (beam and slab reinforcement)

Design for concrete bearing

Estimation of loss of brace prestress due to creep and shrinkage under service load condition

Just after the release of prestressing force

After the loss due to creep and shrinkage

Initial stiffness is due to FSSP device

Axial shortening of a brace

Axial strength of a brace

Design response range

Stiffness of a diagonal element

(c) Axial force-displacement relation of brace

(a) Brace system and its major design issues

(b) Assemblage of flat springs and steel tube

Fig. 1 Prestressed brace system and its resisting mechanism.
design issues are again discussed using the design flow chart later.

2. Evolution of prestressed brace system

2.1 First generation: X-shape precast prestressed concrete brace with a circular center core

The first generation of prestressed concrete brace consists of four precast elements as shown in Fig. 2(a) and the detail information is seen in References (Watanabe et al. 2004, Kono et al. 2005). Precast Element C has a circular core which works as a hub of the diagonal braces. After assembling four elements at a construction site, prestressing force is introduced to two lower legs. Gaps between element ends and frame corners are filled with high strength no-shrinkage mortar. After hardening of mortar, the prestressing force is released. Then the X-shape brace extends and fixed to the boundary frame by itself. When a frame with the brace experiences lateral load, one of diagonal members works effectively in compression and the other diagonal member carries a little or no load. Figure 3 shows lateral load – drift relations of tested specimens shown in Fig. 2(b). Two figures showed the results of two specimens with different axial buckling strengths of braces: the brace of No. 2 had higher buckling strength than that of No. 1. Both No. 1 and No. 2 failed with crushing of the brace concrete. The maximum capacity of No.1 was +397 kN and -410 kN, that of No. 2 was +726 kN. The initial stiffness was 122 kN/mm for No. 1 and 162 kN/mm for No. 2. Both specimens showed elastic response with small energy dissipation till failure. The hysteresis curves show minor slips near the origin. As mentioned earlier the axial stiffness of a brace changes at the point E in Fig. 1(c), that is, the brace shows relatively low stiffness until the re-contact of the steel bearing plate and the steel pipe of FSSP device. Observed slip is mainly due to this abrupt stiffness change. The amount of slip depends on several variables such as the initial prestressing force and the stiffness of FSSP device. The slip does not seem to affect the seismic performance very much. Figure 3 also shows the lateral load carried by frame. The contribution of the original frame was obtained by deducting the

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**Fig. 2** The first generation prestressed brace system (Watanabe et al. 2004).

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**Fig. 3** Lateral load – drift relation of the prestressed brace system (Watanabe et al. 2004).
lateral component of measured brace compressive force from total lateral force where the brace compressive force was calculated by concrete strain measurements. At the peak load, 64 % was sustained by the brace in No.1 and 79 % in No.2, respectively. However, the post-peak behavior for both specimens is brittle since the failure is caused by the compressive failure of the brace as shown in Fig. 4 although the damage of surrounding frame was limited to flexural cracks of beams and columns since the enforced displacement was not very large. Hence, it is not appropriate to anticipate any energy dissipation after the peak and the design should count solely on the strength enhancement. Due to its low cost and ease of construction, the first generation brace system has been used at many school buildings and some office buildings as shown in Fig. 5. For example, it is quite attractive to be able to finish the retrofit work during a two-week winter or spring vacation if the prestressed brace system is employed at schools.

For the first generation brace system, 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 as shown in Fig. 2(a), prestressing force was not very efficiently introduced and it was not possible to take out prestressing rods after the construction. Hence removing the installed prestressed braces was not possible without damaging the brace and frame.

2.2 Second generation: X-shape precast prestressed concrete brace without a circular center core

The second generation of prestressed brace system does not have a circular central core as shown in Fig. 6 (Kono and Watanabe 2006a, 2006b). The brace system consists of four legs and one central unit. Five units are assembled at a construction site and prestressing force is applied along both diagonal directions with external cables as shown in Fig. 7. The gaps between the brace ends and frame corners are filled with high strength and no-shrinkage mortar as the first generation brace system. After the grout mortar hardens, the prestressing force is released so that the brace diagonals extend and securely fit into the existing frame. From this generation, the prestressing force is applied to the whole length of the brace with external rods and the efficiency of introduction of prestressing force was greatly improved. Rods can be reused and the brace can be taken out by reapplying the prestressing force if necessary, making it possible to relocate the brace. The relocation capability is appealing to warehouse structures which occasionally change the live load configurations.

Two-story braced specimens in Fig. 6(b) were built and tested to see the behavior under cyclic lateral load when the multi-story frame with the second generation bracing system experiences overall cantilever type deformation. Details of experiment can be seen in References (Kono and Watanabe 2006a, 2006b). The ultimate failure was caused by the tensile yielding of the first story column and the load-drift relation after the yielding was greatly enhanced as shown in Fig. 8. Specimen E1 had much larger deformation capacity after the peak. This large deformation capability was made possible by tensile yielding of the first story columns. Stiffness of the frame decreased first when the flexural cracking started at drift angle (R), R = ±0.05 %, then again when...
longitudinal bars of columns started to yield at R=±0.4%. The maximum lateral load in positive direction, +324 kN, was recorded at R=+1.5%. The force in the diagonal brace at the first floor was computed from the mean strain measured with strain gages on all four brace surfaces and the stress-strain relationship obtained from a cylinder compression test. The horizontal component was subtracted from the total lateral load to obtain the contribution due to the two columns of the original frame. The portion of the lateral load carried by the original frame is compared to the total load carried by the braced frame. The lateral load carrying capacity of braced frames was nearly three times larger than that of the original bare frame as Specimens No. 1 and 2. Specimen E1 also shows some slip near the origin due to the loose contact of FSSP device as Specimens No.1 and 2 but a small amount of slip is considered permissible. The ductility of Specimen E1 is much greater than the first generation brace system. An example of the second generation is shown in Fig. 9. Since the volume of concrete decreases, the brace blocks out less view and more light can pass the retrofitted span.

2.3 Third generation: Single line prestressed brace using concrete filled tube or fiber reinforced concrete

The third generation of prestressed brace system is a single line element as shown in Fig. 10 (Kono and Watanabe 2007a, 2007b). Materials of the brace were either concrete filled tube (CFT) or fiber reinforced concrete (FRC) to increase the deformation capability so that the brace does not exhibit sudden drop of load after the peak load. The details of experiment are shown in References (Kono and Watanabe 2006a, 2006b). Loading system is shown in Fig. 11. Fig. 12 shows the lateral load – drift relations for CFT (CFT-S60) and FRC (FRC-L30) braced frames. For CFT-S60, the initial stiffness changed when cracking was observed at the left (left in Fig. 10 and Fig. 11) 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 left 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 started to buckle 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 did not happen. On the other hand, the load – drift relation of FRC-L30 was stiffer than that of CFT-S60 because of the larger section size of the brace. The reinforced concrete portal frame of FRC-L30 showed the first cracks at the left column-beam joint at R=0.2%. The load carrying capacity increased up to R=0.6%. After that, drift angle increased with keeping the load carrying capacity almost constant. At this stage, large diagonal bearing and shear cracks were observed at the left column-beam joint and the brace started to
penetrate the left column-beam joint. Minor cracks parallel to the axial direction were observed in the brace at $R=0.8\%$. The brace of FRC-L30 was so strong that it penetrated the left column-beam joint by 20 to 30 mm. FRC-L30 failed due to the shear or bearing failure of the left beam-column joint.

CFT-S60 showed gradual degradation of load after the buckling occurred at the spliced mid span. FRC-L30 reaches the peak load at drift angle of 0.8\%, whereas Specimens No. 1 and No. 2, which employed the ordinary precast concrete as shown in Fig. 3, reached the peak at drift angle less than 0.6\%, and the effect of fiber can be seen. However, FRC-L30 shows the rapid degradation after the compressive failure has occurred at the mid span.

The configuration of the third generation was changed to a line element so that the brace aesthetically looks better and a door opening can be made at the braced span if necessary. Since a line element can resist against force in a single direction and does not work in opposite direction, it is necessary to place braces for the opposite direction at some other spans. However, placing simple line elements instead of X-shape elements saves construction time and labor. In addition, CFT has more advantages 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, then the inside of the steel tube is filled with grout mortar. In this way, CFT necessitates the minimum amount of construction materials and excludes heavy construction equipment.

3. design and construction

3.1 Design procedures
The proposed design procedure (Kono and Watanabe 2008) is shown in Fig. 13. The possible ultimate failure modes of braced frame include five modes: (1) buckling of diagonal members, (2) joint shear failure, (3) tensile failure of beams, (4) tensile or compression failure of the first story column when the multiple-story brace system, and (5) the rocking mode of the foundation. The buckling of diagonal members is designed to precede the other failure modes to avoid the damage to the structural components in the existing buildings. The buckling strength needs to take into account the initial imperfections of the diagonal members. All possible
failure modes are sequentially checked based on the design flow in Fig. 13. After the determination of the ultimate failure mode, the initial prestressing force of the brace is determined considering the prestressing loss due to the shrinkage and creep. The number and location of braces and the structural type of existing buildings also influence the initial prestressing force. Main consideration at design is the determination of the ultimate failure mode, computation of the lateral load carrying capacity and displacement capacity, determination of the initial prestressing force, and determination of the mechanical properties of FSSP (flat spring-steel tube).

3.2 Construction methods

There are two ways to introduce prestressing force to braces: pre-tensioning and post-tensioning. For a pre-tensioning system, the prestressing force is introduced to the assembled braces with external cables, the...
assemblage is placed inside the frame, the gap between the assemblage and the surrounding frame is grouted, and the external cables are released and taken out. On the other hand, the post-tensioning system, the assemblage of brace is placed inside the frame, the gap is grouted, and the hydraulic jack is used to introduce prestressing to the assemblage. The threaded steel tube is extended to fill the gap made after the introduction of prestressing force. It is possible to relocate both pre-tension and post-tension systems. By re-applying the prestressing force to the brace assemblage, the assemblage shortens and can be removed from the position. The same procedure may be taken to put the assemblage in a new location.

3 Conclusions

Prestressed brace system was proposed to retrofit existing buildings vulnerable to seismic damage by basically increasing the strength. The system is recognized as a quick, easy and economical retrofit method since it employs no bolt anchorage. The system has been frequently used at school buildings for its short construction period. The paper introduces the evolution of the system since 2001. The current system has ductility, re-location ability and easier construction using advanced materials. The good seismic performance of the system has been proved through experiment and analysis from their first introduction.

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