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Shear Performance of Fiber-Reinforced Cementitious Composites Beam-Column Joint Using Various Fibers

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ABSTRACT

Increasing demands of reinforcement in the joint panel are now requiring more effective system to reduce the complicated fabrication by widely used precast system. The joint panel is responsible to keep the load transfer through beam and column as a crucial part in a structural frame that ensures the main feature of the whole structure during earthquake. Since precast system might reduce the joint panel monolithic integrity and stiffness, an innovation by adding fiber into the grouting system will give a breakthrough. The loading test of precast concrete beam-column joints using FRCC (Fiber-Reinforced Cementitious Composites) in joint panel was conducted to evaluate the influences of fiber towards shear performance. The experimental factor is fiber types with same volume fraction in mortar matrix of joint panel. Two specimens with Aramid-fiber and PP-fiber by two percent of volume fraction are designed to fail by shear failure in joint panel by reversed cyclic testing method. The comparison amongst those experiment results by various parameters for the shear performance of FRCC beam-column joints using various fibers are discussed. Preceding specimens was using no fiber, PVA fiber, and steel fiber has been carried out. Through the current experimental results and the comparison with previous experiment results, it can be recognized that by using fibers in joint panel was observed qualitatively could prevent crack widening with equitable and smaller crack width, improved the shear capacity by widening the hysteretic area, increased maximum load in positive loading and negative loading, and decreased the deformation rate. Elastic modulus properties of fiber are observed to give the most impact towards shear performance.

Keywords: Joint panel, fiber, FRCC, elastic modulus, shear performance

1 INTRODUCTION

Current concrete building constructions presently show trend in demand to use more efficient ways to ease the workmanship but still achieves same performance. Nowadays, precast system (Figure 1) is commonly used in most of construction works because its ease of workability, cost efficiency, and time efficiency. The general utilization of precast system is mostly for beams and columns, while beam-column joints consistently used conventional cast in-situ method. Development of polymer material and synthetic fibers has become a trigger to use them to improve structural performance and damage resistance without a corrosion problem. Research on flexural strength of column using polymer material or resin concrete was conducted by (Patah, et al., 2016). From the results of the previous research, application of polymer resin concrete could restore and even increased the strength of column.

Fiber-Reinforced Cementitious Composites (hereafter referred to FRCC) is cementitious materials reinforced with short discrete fibers that are distributed in matrix. It is well known that FRCC shows high ductility under tensile and bending stress condition. Hence, research about FRCC based material that is mixed with various fibers has been actively developed in these recent years (ACI Committee, 2001). The previous study reported that the shear performance of beam-column joint using FRCC is improved compared to non-fiber beam-column joint (Sano, et al., 2016). Another study also reported that by using steel fiber and polyvinyl alcohol (PVA) fiber for FRCC also improves the shear performances Ando, et al. (2016), and Yamada, et al. (2016)

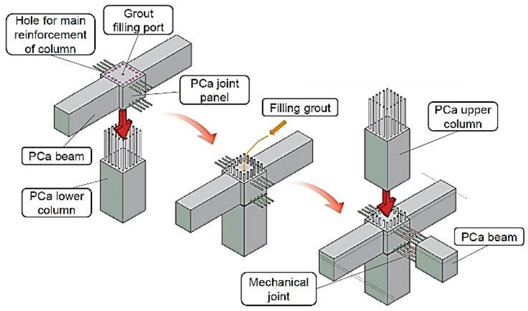


Figure 1. Precast system (Sano, et al., 2015)

Increasing the demand of reinforcement in the joint panel is now requiring more effective system to reduce the complicated fabrication and to retain a good structural performance. Beam and column joint is a crucial part of a structural frame that ensures the main feature of the whole structure. Although beam and column are still in the state of inelastic, joint should retain the ability to bridge the structural actions. Figure 2 shows a critical damage of a structure in joint panel area caused by earthquake. While beam and column are cast separately and constructed by grouting the joint area, this method will lessen the monolithic characteristic compared to conventional method. At the other hand, based on Shiohara (2001) stated that the most common case of stiffness reduction is due to the formation of diagonal cracks and local crushing of concrete. That failure case of beam-column connection must be prevented to preserve the structural integrity of members joined as rigid and strong that commonly assumed in structural analysis. The usage of FRCC in the joint panel would give a solution to fulfill these problem requirements (Hanif, 2017).

Figure 2. Joint panel damage caused by earthquake (Guner, 2016)

The advantages of precast system are still limited in joint panel area. Those various fibers utilization suggested to increase ductility, crack behavior, deformation behavior, and shear capacity prior to suppressing damages. Therefore, further research on this topic is indispensable to consider the influence towards each fiber types. This present study has been prepared two fiber types, namely aramid fiber and polypropylene (PP) fiber to be mixed into the matrix of FRCC beam-column joint specimens. Experiment results from previous study (non-fiber, PVA fiber, and steel fiber) also will be included in this report with intention to compare among those fiber's influences. Those fiber types were chosen by the market availability as consideration.

The full-scale experiment was conducted to represent the real practical condition in construction. Thus, specimens which have fiber types as variation factor was designed to fail by shear failure in joint panel, was conducted to evaluate the performance of the joint panel. The observation scope of fiber influences as follows:

a) Physical damage resistance based on crack patterns
b) Structural performance as shear capacity
c) Structural performance as deformation rate
d) Structural performance as equivalent viscous damping ratio

This study is conducted to provide information about the shear performance of several fiber types (PVA fiber, steel fiber, PP fiber, and aramid fiber) to show which fiber that has better practical application. Based on those results can be shown the benefit of FRCC usage compared to conventional concrete.

2 PREVIOUS RESEARCH

Research on fiber-reinforced cementitious composites has actively been conducted in many fields. The most used variable scopes are volume fraction are fiber types. This research significance is focused on fiber types based on this following previous research. The main reference of this study is based on the previous research conducted in the same laboratory as this research.

FRCC is cementitious materials reinforced with short discrete fibers that are distributed in matrix. Ductile Fiber-Reinforced Cementitious Composites (DFRCC) are defined as cementitious composite material reinforced with fiber, which shows multiple cracking characteristics under bending stress and features drastically improved ductility during bending, tension, and compression failures. High-Performance Fiber-Reinforced Cementitious Composites (HPFRCC), which show a strain hardening branch and multiple cracking under uniaxial tensile stress, are included in DFRCC. It is important to evaluate and express the characteristics of DFRCC with suitable methods to enable the use of DFRCC for actual applications taking advantages of the merits of these composite materials (Kanakubo, 2006).

Shimizu, et al. (2004) published a research of bending shear test and uniaxial tensile test of PVA-ECC specimens. Crack patterns presented in Figure 1 (from left: no fiber, 1%, 1.5%, and 2% of PVA fiber) was observed to be better distributed along with smaller crack width as volume fraction increases.

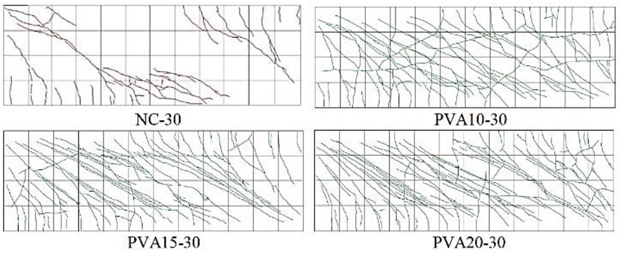


Figure 1. Crack patterns at 0.01rad (Shimizu et al., 2004)

Kanakubo, et al. (2007; 2010) published the result of loading test for PVA-ECC beam specimen by bending shear test and uniaxial tension test. From this experiment, shear strength increases as volume fraction of PVA fiber increases. An experiment conducted by Shimizu, et al. (2004) reveals that shear strength increases as volume fraction of PVA fiber increases (Figure 2). Based on other experiment result published in (Sano, et al. (2015) and Yamada, et al. (2016) concluded that fiber could inhibit the damage of joint panel by the increment of shear force carried by the bridging effect of fibers. Fiber bridging effect gives tensile strength addition to prevent more of crack widening.

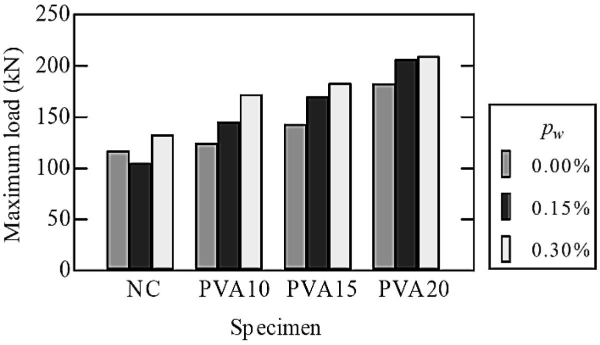


Figure 2. Comparison of maximum strength

3 THEORETICAL BASE

3.1. Shear Failure of Beam-Column Joints

Earthquake resistant design for reinforced concrete frames in terms of to design the beam-column joint as a moment resisting frames is an important groundwork for this research. The basic shear design on this experiment is considering beam-column joint connection not as a rigid platform (versus the common calculation assumption nowadays) and concerned to provide the specimen with stiffness and sufficient strength to sustain the load transmission through beam and column at joint panel area. The main discussion about shear failure in this experiment is focused on this following design concept.

The shear failure design concept was adopted from Shiohara (2001). This publication stated that joint shear in beam-column connection acts as a horizontal force transferred at the mid-height of a horizontal section of a beam-column joint (refers to Figure5 and Figure6). Joint shear failure is suggested that might be precluded by limiting the joint shear stress to the level at which joint shear failure will occur. Per this limitation, the joint stiffness reduction due to shear stress can be prevented by reducing the formation of diagonal cracks and local crushing of concrete.

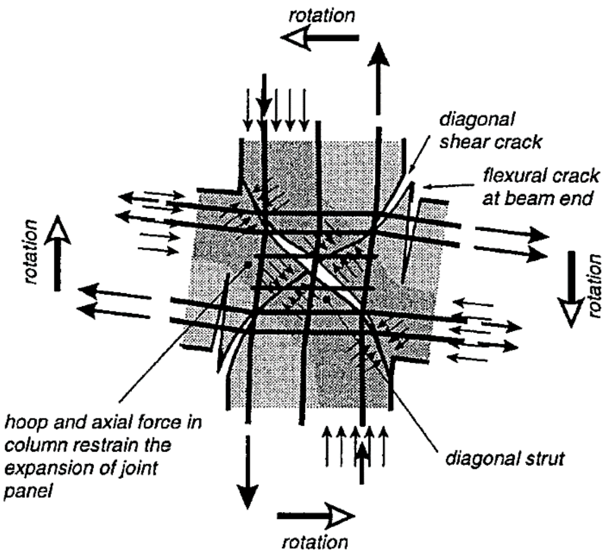
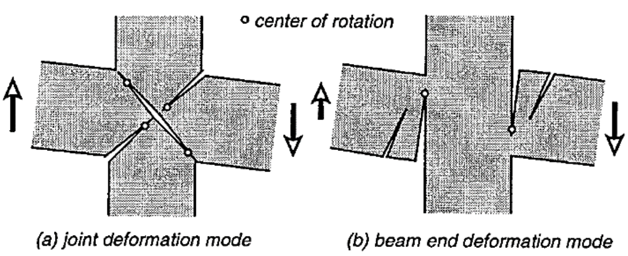


Figure 5.Example of behavior model for joint shear failure (Shiohara, 2001)



(a) joint deformation mode (b) beam end deformation mode

Figure 6. Example of behavior model for beam-column connection failure (Shiohara, 2001)

The further limitation between joint shear stress towards joint shear failure can cause the joint shear failure itself to occur (Figure 7). This experiment suppressed in this basic idea to make a shear failure.

Thus, the fiber effect in joint panel area that has been observed is a genuine effect caused by shear failure.

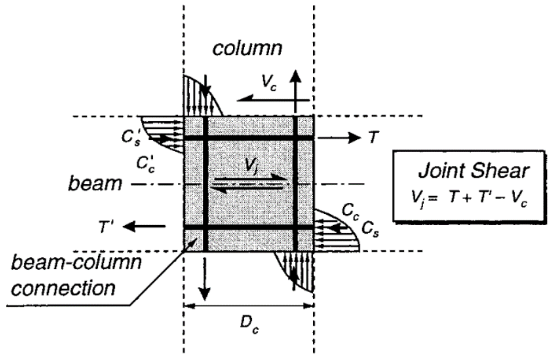


Figure 7. Horizontal joint shear in interior RC beam-column joint

3.2. Reversed Cyclic Loading Method

These test methods are designed to evaluate the capacity of this full-scale specimen under static cyclic reversed load conditions. The cyclic method gives the load in positive and negative directions by the drift angle as loading reference. This research was done by two-cycle method in each drift angle in positive and negative directions. The reversed method refers to carry out the reversed drift angle in each cycle from positive to negative of the same drift angle. This cyclic loading method is a loading model that approach the real condition towards static load during earthquake. The example of cyclic loading method is shown in Figur 8.

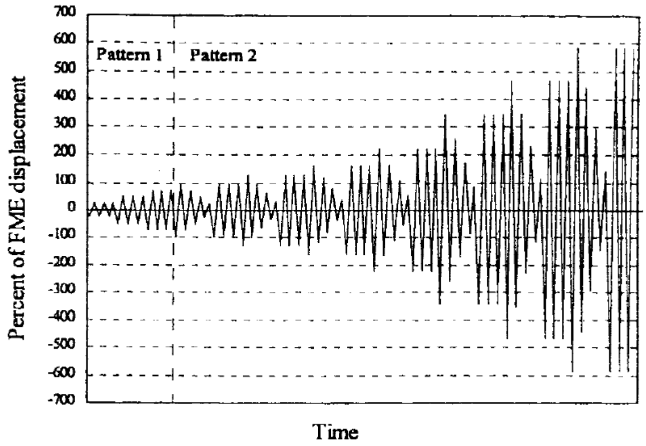


Figure 8. Sequential-phased displacement cyclic displacement (ASTM International, 2002)

3.3. Load-Drift Angle Curve (Hysteresis Curve)

Hysteresis curve is obtained from reversed cyclic load that was done on specimen to show the increment of load and drift angle deviation while reaching the desired drift angle in each cycle (Figure 9). The flatter hysteretic loop in each cycle indicates the lower shear behavior towards applied load. Based on this curve can be observed the internal energy that has been absorbed or released. Skeleton curve used in this result section shows the outer section of hysteretic lines to observe the highest hysteretic result.

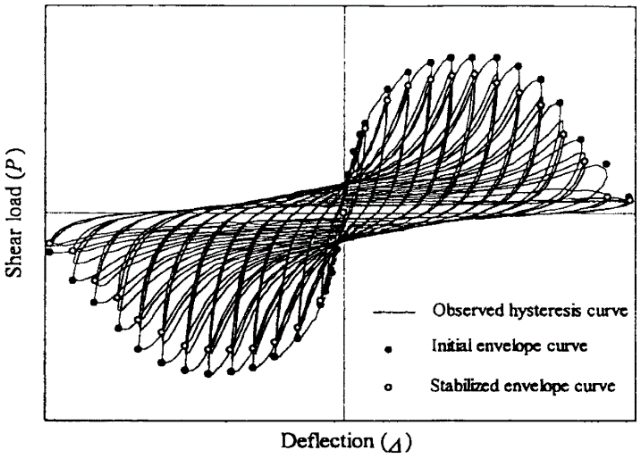


Figure 9. Observed hysteresis curve and envelope curves (ASTM International, 2002)

3.4. Equivalent Viscous Damping Ratio

Damping ability of structure is modeled as viscous damping. The damping coefficient is stated as damping ratio that shows the level which is held by each structure to absorb or release energy corresponding to physical deformation, fatigue, and structural damage caused by external force. The higher damping ratio value, the higher ability of structure to absorb energy. Effective damping will much reduce or eliminate the structural shake. Equivalent viscous damping ratio (EVDR) is calculated by equation as follows.

$$EVDR = \frac{W_D}{2\pi \cdot U_0} \quad (1)$$

Damping energy (W_D) is a total area of enclosed curve in hysteretic loops in each cycle, where the absorbed energy level in each cycle show the structure ability to absorb and reduce the given external force. Strain energy (U_0) is the maximal energy or internal force that held within the structure caused by external force which is enabling structure to deform. Strain energy in each cycle is the total area of triangle ABC and AED as shown in Figure 10. Hysteresis loop resulted from experiment often asymmetrical because of random effect during the loading time. Therefore, the area of triangle ABC and ADE were averaged to obtain strain energy.

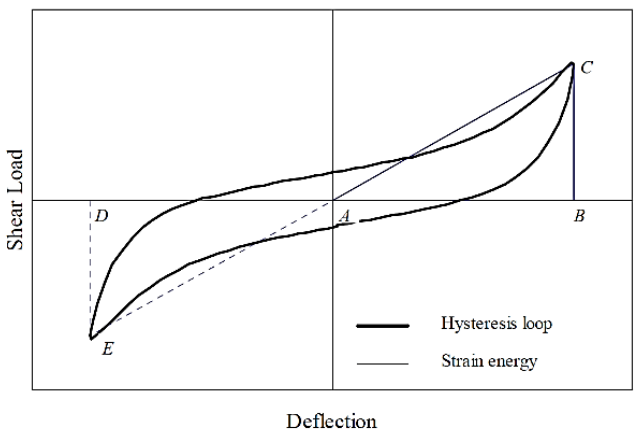


Figure 10. Damping and strain energy of a cycle (American Iron and Steel Institute, 2007)

3.5. Shear Capacity

Shear capacity in this experiment defined as an absolute value of the whole structure to retain maximum load of shear force in each cycle in hysteresis curve. Accordingly, this absolute value will be compared towards other fiber type specimens or design calculation value. The shear capacity values are taken directly from the experiment measuring equipment.

4 RESEARCH METHOD

4.1. Specimen

Specimens identities are listed in Table 1, and Figure 12 shows the dimension of specimens. The internal beam-column joint in practical application of buildings is scaled as beam section by 380mm x 420mm and column section by 500mm x 500mm. The experimental factors are various type of fiber with the same volume fraction of 1.0% in joint panel with similar specimen's design. Previous experiments have specimen No. 24 without fiber, No. 25 with PVA fiber, and No. 28 with steel fiber. Present experiment has specimen No. 30 with aramid fiber and No. 31 with PP fiber.

Table 1. Specimen list

ID	Fiber type & volume fraction (%)
No. 24*	No fiber
No. 25*	Polyvinyl alcohol (PVA) 1%
No. 28*	Steel 1%
No. 30	Aramid 1%
No. 31	Polypropylene (PP) 1%

(*) From previous studies (Sano, et al., 2015) (Ando, et al., 2016)

Those specimens are designed to fail by shear failure in joint panel to evaluate the shear performance. This experiment is intended to observe the shear capacity by only fiber's factor in FRCC, the stirrups are not used in joint panel. Therefore, distinct fiber effect in joint panel that has been observed isn't influenced by stirrups reinforcing strength ability. The casting of joint panel and beam-column were done separately to represent the precast system. The upper picture shows the first step of casted joint panel with FRCC, and the lower picture shows the second step of casted beam and column with normal concrete. The used casting material is classified in two categories distinguished by casting place. Joint panel area was using mortar as FRCC and beam-column area was using ordinary concrete. The differentiation between mortar and concrete is in the presence of coarse aggregates, where concrete uses coarse aggregates and mortar is absence of coarse aggregates. Volume fraction defined as a total volume calculated by specific weight divided by total volume of mixture. FRCC mix proportion is better to have volume fraction by less than 2% (based on several types of research).

There are two different types of fiber-reinforcing usage, those are continually reinforced and discrete short fibers. This experiment will use discrete short fibers (less than 50mm long) usage which are incorporated in the matrix by mixing method. Mechanical properties of various fiber types are described in Table 2 and Table 3. The visual appearance of used fibers is shown in Figure 11.

Table 2. Mechanical properties of concrete and FRCC

Type	Specimen	Place	Compressive strength (MPa)	Splitting tensile strength (MPa)	Elastic modulus (GPa)
Concrete	No. 24	Beam and column	39.9	3.55	29.6
	No. 25		39.1	3.42	28.0
	No. 28		89.4	5.57	38.4
	No. 30		83.4	4.09	37.1
	No. 31		72.8	4.15	38.0
FRCC	No.24	Joint panel	50.3	2.55	17.6
	No. 25		52.5	-	17.1
	No. 28		56.8		18.7
	No. 30		51.3		17.7
	No. 31		51.5		17.2

Table 3. Mechanical properties of fiber

Fiber	Length (mm)	Diameter (mm)	Tensile strength (MPa)	Elastic modulus (GPa)
Polyvinyl alcohol (PVA)	12	0.1	1200	28
Steel	13	0.16	2830	210
Aramid	30	0.5	3432	73
Polypropylene (PP)	30	0.7	580	4.9

Figure 11. PVA, steel, aramid, and PP (from left)

a) Polyvinyl Alcohol (PVOH or PVA) is a water-soluble white (colorless) and odorless synthetic polymer. Usually used in papermaking, textiles, and a variety of coatings.

b) Steel Fiber is generally carbon steels or alloy (may include carbon (C), silicon (Si), manganese (Mn), phosphorus (P), sulfur (S), and other elements). Steel fiber has become the most commonly-used fiber concrete, though it is fast being overtaken by other synthetic fiber reinforced concrete (Bentur & Mindess, 2007). Common uses of steel fiber besides as an FRCC are such as protective suits, space suits, and cut resistant gloves for butchers and other people working near bladed or dangerous machinery.

c) Polypropylene (PP) is a thermoplastic polymer used in a wide variety of applications including packaging and labeling, textiles (e.g., ropes, thermal underwear, and carpets), stationery, plastic parts and reusable containers of various types, laboratory equipment, loudspeakers, automotive components, and polymer banknotes.

d) Aramid fibers are a class of heat-resistant and strong synthetic fibers. Aramid is used in aerospace and military applications, for ballistic-rated body armor fabric and ballistic composites, in bicycle tires, and as an asbestos substitute.

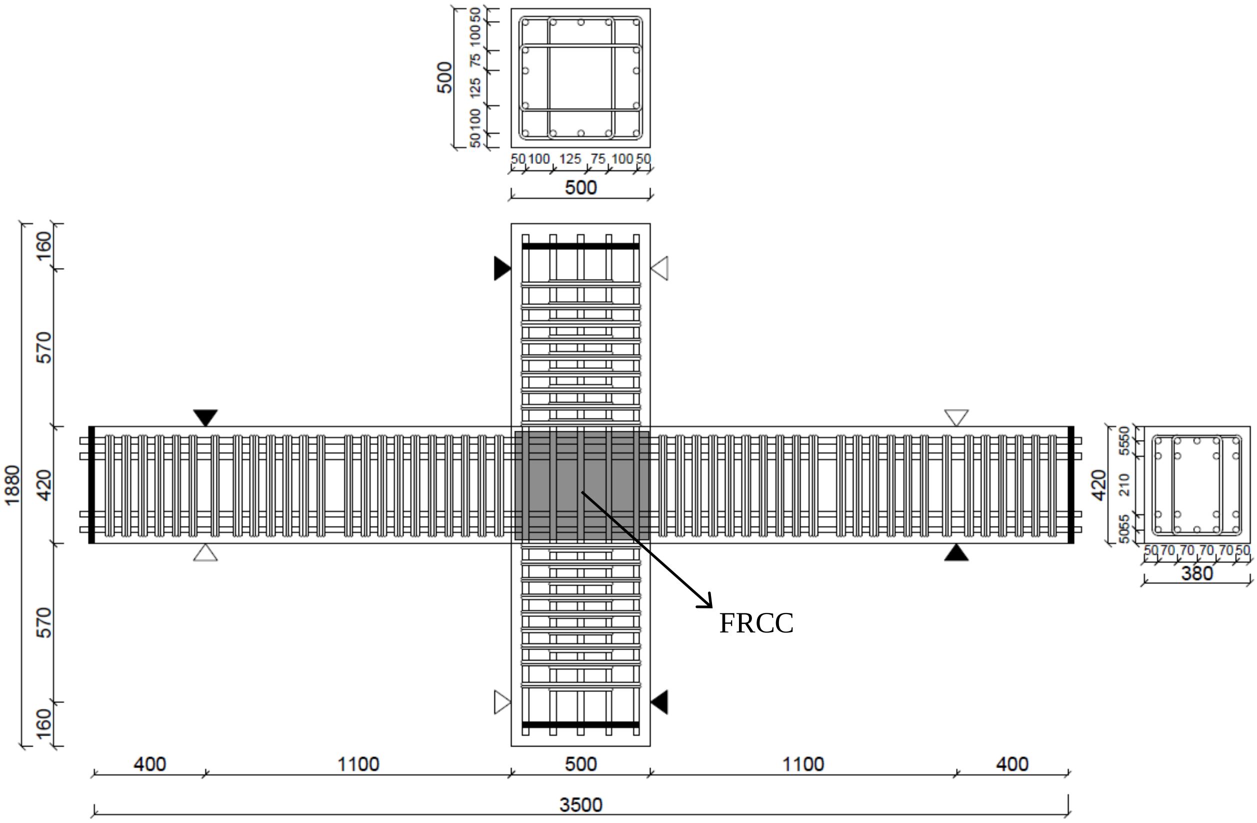


Figure 12. Specimen dimensions

4.2. Loading and Measurement Method

Columns end are supported by oil jacks at the designated inflection point to give a static reaction. Story drift angle is controlled by hydraulic actuators on the designated inflection point of beams. Those actuators are responsible to reverse cyclic load with a target of story drift angle by R = ±1/400, ±1/200, ±1/100, ±1/67, ±1/50, ±1/33, ±1/25, ±1/20 and +1/14 rad shown in

Figure 13. Story drift angle (α) is detected by LVDT. The LVDTs to measure story drift angle are shown in Figure 14.4, while to measure local deformation, The LVDTs are shown in Figure 155.

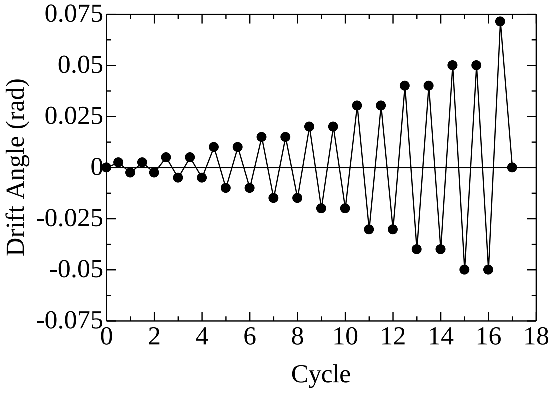


Figure 13. Loading cycle

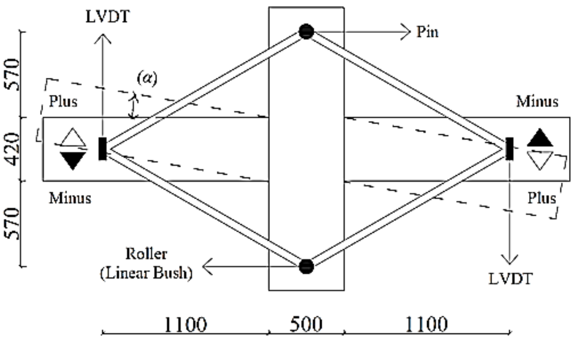


Figure 14. Measurement of story drift angle

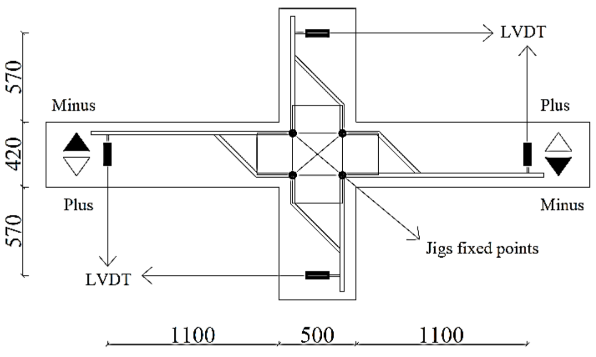


Figure 15. Measurement of beam and column local deformations

5 RESULT AND DISCUSSIONS

This experiment conducted Specimen No. 30 and No.31 (PP fiber and aramid). Results from Specimen No. 24, No. 25, and No. 28 (no fiber, PVA fiber, and steel fiber) are obtained from previous studies (Sano et al., 2015, Ando, 2016) and presented in this section to give better comprehension.

5.1. Crack Patterns

Figures presented in Figure 17 show the transition of the crack patterns of joint panel area according to the peak step of each drift angle on each fiber types. From these following photos by visual observation, can be described that specimen with no fiber has the most severe performance and specimen with PVA fiber has the most excellent performance in term of damage resistance based on crack patterns by having the equitable and smaller crack width around the maximum load.

5.2. Local Deformations

Local deformation is calculated by comparing between total deformation obtained from the beam, column, and joint panel and each member's deformation. Maximum deformation rates at joint panel would achieve the highest number when maximum load occurred. Based on Figure 16, it can be observed around the maximum load, deformation rate of joint panels in specimens with fiber are showing reduction compared to the specimen without fiber. Most of joint panel deformation in the specimens with fibers is lower than that without fiber. Thereafter, it can be considered that fibers prevent the shear crack in joint panel to increase.

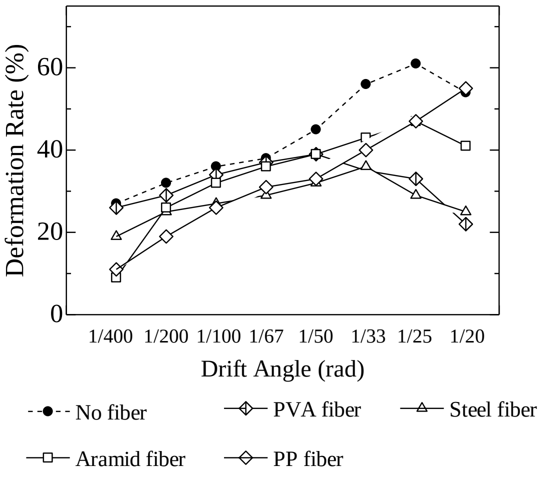


Figure 16. Deformation rates by specimens

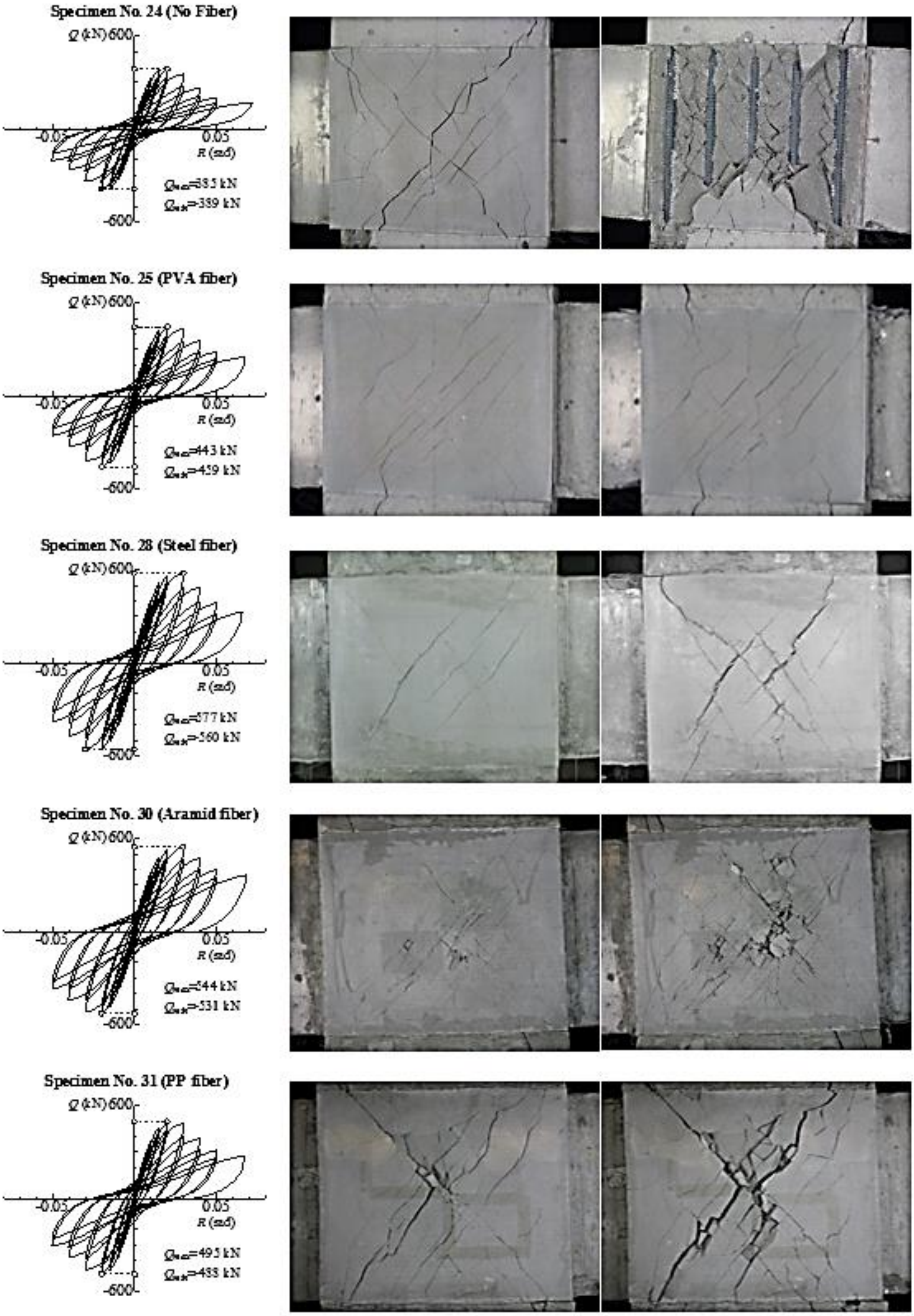


Figure 17. Q-R Relationship and crack patterns (left: 1/50 rad, right: 1/33 rad)

5.3. Shear Capacity of Joint panel

Experiment and calculated values of each specimen are shown in Table 4 and Figure 18. Those calculated values of beam bending capacity, column bending capacity and shear capacities are calculated using predicting formulas as the same as conventional concrete specimen calculation (Architectural Institute of Japan, 1999). After comparing the predicted shear force (panel joint shear capacity) versus experiment results (maximum load), all the specimens confirmed that experimental value is higher than calculated value. Based on this result, due to fiber adding into mortar matrix is considerable to increase the shear capacity.

Table 4. List of calculation & experimental value in kN

Specimen	No. 25	No. 28	No. 30	No. 31
Panel joint shear capacity from calculated values (*)	434	456	423	426
Maximum load from experiment results	459	577	544	495

(*) without fiber contribution

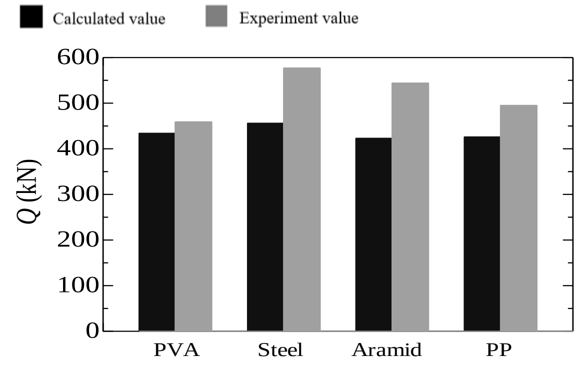


Figure 18. Shear capacity values of each fiber type of specimens

5.4. Story Drift Angle and Shear Force Relationships

The skeleton curve of Q-R relationship is simplified in Figure 19. 17 and can be observed that specimen with various fiber types has widened the maximum load and hysteretic area. Figure 17 shows relationship between applied loads versus story drift angle (hysteretic curve). Each specimen with different fiber types has different drift angle of maximum load. The maximum load was observed at 1/50 in specimens without fiber, with PVA fiber, and with PP fiber. Specimens with steel fiber and aramid fiber have maximum load at drift angle of 1/33. Based on mechanical properties of various fiber types in Table 3, Aramid fiber has the highest tensile strength followed by steel fiber, PVA, and PP sequentially. Steel fiber has the highest elastic modulus followed by aramid, PVA, and PP sequentially. Based on Figure 19, steel fiber could be considered to have highest shear performance because steel fiber has the highest mechanical properties in term of elastic modulus and afterward followed by aramid fiber which has second highest of elastic modulus, then followed sequentially by PP fiber and PVA fiber. Eventually, joint panel without fiber has lowest shear performance. Therefore, it is considered that elastic modulus of fiber would influence the shear performance.

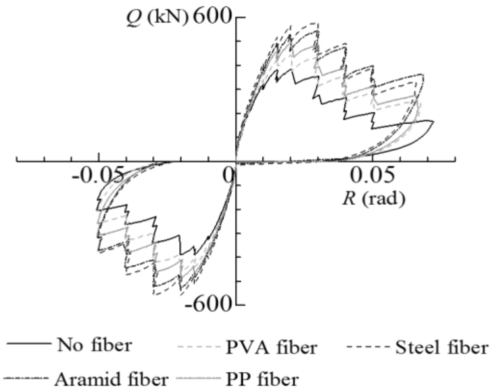


Figure 19. Q-R relationship by various fiber types in skeleton curve

5.5. Maximum Load

Figure 20 shows that the maximum load of specimens with fiber are higher than that of without fiber. After the maximum load, shear crack width was increasing and the peak load of each loading cycle started to decrease due to shear failure in joint panel. As previously described, elastic modulus of fiber is considered to influence the shear performance. Steel fiber has the highest elastic modulus followed by aramid, PVA, and PP sequentially. Steel fiber has the most excellent performance among all those fiber types followed by aramid fiber, PP fiber, PVA fiber, and specimen with no fiber has the poorest performance. Based on these results, it is considered that shear performance of joint panel is improved due to the influence of elastic modulus of fiber.

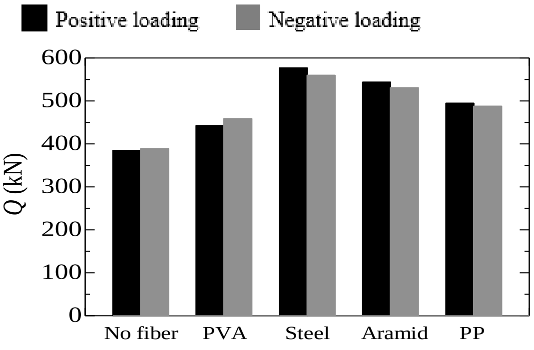
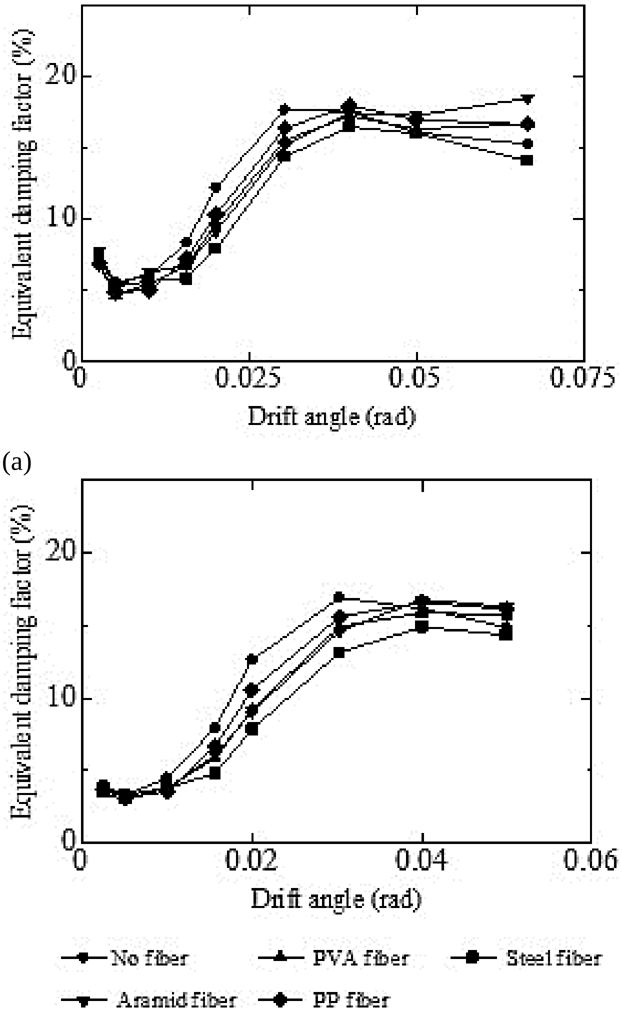


Figure 20. Maximum load of each fiber type of specimens

5.6. Equivalent Viscous Damping Ratio

The equivalent viscous damping ratio in each loading cycle is shown in Figure. Specimens with fibers show an insignificant effect compared to the specimen without fiber. All specimens show a similar trend line along with drift angle that specimens with fiber are just slightly decreased in equivalent viscous damping ratio. For example, the equivalent viscous damping ratio in first and second cycle at the maximum peak of 1/50 and 1/33 are observed slightly decreased. The equivalent viscous damping ratio results are still vary depending on fiber type. Based on this result, by the adding of fiber into the matrix would give insignificant impact towards equivalent viscous damping ratio.



(b)

Figure 19. Equivalent viscous damping ratio (heq) of (a) 1s loading cycle, and (b) 2nd loading cycle

The first cycle of specimen with no fiber is ranged between 12.2% until 17.7%, while specimen with fibers are ranged between 7.9% until 16.4%. Followed by the second cycle of specimen with no fiber is ranged between 12.6% until 16.9%, while specimen with fibers are ranged between 7.8% until 15.6%. The equivalent viscous damping ratio results are still vary depending on fiber type with the differentiation range is just ranged about 1.3% until 4.8%. Based on these results, fiber adding would give insignificant effect towards equivalent viscous damping ratio. The slight effect of equivalent viscous damping ratio will still need a further research.

6 CONCLUSIONS

a) The expansion of crack width due to shear force was observed to be inhibited by adding fibers in joint panel area. Among the various types of fiber, PVA fiber has the most excellent performance in term of damage resistance based on crack patterns with equitable and smaller crack width around maximum load.
b) Shear capacity of joint panel without fiber is increased by the effect of fiber types. Among the various types of fiber, steel fiber shows the greatest shear capacity with the widest area of hysteretic area.
c) Most of deformation rate in specimens with fibers were decreased along with drift angle, compared to those without fiber.
d) The fiber adding would give insignificant impact towards equivalent viscous damping ratio with the differentiation range is just ranged about 1.3% until 4.8%.
e) Mechanical properties of each fiber types, especially elastic modulus properties are observed to give the most impact towards shear performance compared to tensile strength properties.

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