รายงานวิจัยฉบับสมบูรณ์

โครงการ การเสริมกำลังรับแรงเฉือนของคานคอนกรีตเสริมเหล็กด้วยคอนกรีตเสริมเส้นใย

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ธันวาคม 2560

สัญญาเลขที่ TRG5880231

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โครงการ การเสริมกำลังรับแรงเฉือนของ
คานคอนกรีตเสริมเหล็กด้วยคอนกรีตเสริมเส้นใย

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สนับสนุนโดยสำนักงานกองทุนสนับสนุนการวิจัยและ
จุฬาลงกรณ์มหาวิทยาลัย

Abstract

Project Code : TRG5880231

Project Title : การเสริมกำลังรับแรงเฉือนของคานคอนกรีตเสริมเหล็กด้วยคอนกรีตเสริมเส้นใย

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บทคัดย่อ :

งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษากำลังรับแรงของคานคอนกรีตเสริมเหล็กเสริมกำลังรับแรงเฉือนด้วยแผ่นคอนกรีตเสริมเส้นใยเหล็กโดยการทดสอบและการวิเคราะห์ตามระเบียบวิธีไฟไนต์เอลิเมนต์ โดยทำการเตรียมตัวอย่างคานคอนกรีตและติดตั้งแผ่นคอนกรีตเสริมเส้นใยสำเร็จรูปความหนา 10 มิลลิเมตรที่ด้านข้างของคานเพื่อเสริมกำลังรับแรงเฉือน แล้วนำไปทดสอบการรับแรงจนกระทั่งวิบัติ ตัวแปรที่ศึกษาคือ ปริมาณเส้นใย ชนิดของรอยต่อ จำนวนและขนาดสลักเกลียว นอกจากนี้ได้วิเคราะห์ตามระเบียบวิธีไฟไนต์เอลิเมนต์ และเปรียบเทียบการวิเคราะห์กับผลการทดลอง จากผลการวิเคราะห์พบว่าแบบจำลองสามารถให้ค่ากำลังรับแรงเฉือนของคานคอนกรีตเสริมเหล็กที่เสริมกำลังได้ใกล้เคียงกับผลการทดลอง จากนั้นจึงทำการศึกษาตัวแปรที่มีผลต่อกำลังรับแรงเฉือนของคานคอนกรีตเสริมเหล็กเสริมกำลังรับแรงเฉือนด้วยแผ่นคอนกรีตเสริมเส้นใยเหล็ก ได้แก่ ความหนาของแผ่นคอนกรีตเสริมเส้นใยเหล็ก กำลังรับแรงอัดของแผ่นคอนกรีตเสริมเส้นใยเหล็ก และการจัดเรียงตัวของสลักเกลียว จากผลการทดลองและการวิเคราะห์พบว่ากำลังรับแรงเฉือนของคานหลังเสริมกำลังเพิ่มขึ้น 1.85-2.05 เท่าเมื่อเทียบกับคานที่ไม่ได้รับการเสริมกำลัง ดังนั้นแผ่นคอนกรีตเสริมเส้นใยเหล็กเป็นหนึ่งในวิธีที่สามารถซ่อมแซมและเสริมกำลังได้อย่างมีประสิทธิภาพ

Abstract :

Shear performance of reinforced concrete beams strengthened with steel fiber reinforced concrete (SFRC) panels was investigated by experiment and numerical analysis. SFRC precast panels were attached to side of RC beams in order to enhance shear capacity of the beams. Series of RC beams strengthened by SFRC panels were tested under four point loading test to determine effects of fiber volume fraction, connection type, number and diameter of bolts. A three-dimensional nonlinear finite element analysis was also conducted in order to obtain a better understanding of shear behavior of strengthened RC beams. Good agreement was achieved between the experimental and analytical results especially for the ultimate load of RC beams. In addition, parametric study was performed to investigate effects of panel thickness, compressive strength of SFRC, and bolt pattern. The experimental and numerical results show that shear capacity of RC beams significantly increased after strengthening by SFRC panels. As a result, strengthening by SFRC precast panels is one of efficient techniques to improve shear capacity of RC beams.

Keywords : Fiber reinforced concrete; Shear; Strengthening; Experiment; Finite element analysis

เนื้อหาและสรุปผลการศึกษา

1. Introduction

The deterioration of reinforced concrete (RC) structures has increased nowadays due to the degradation of structural materials, the increase in design load or suffer from disaster. However, only few RC structures have been strengthened or repaired. In the near future, a number of RC members requiring for strengthening or repair are going to increase significantly. In order to prepare for upcoming-retrofitting era, it is important to develop the strengthening and repair techniques as well as to investigate the load carrying capacity of RC members after strengthening in order to ensure safety of structures.

One of the common strengthening techniques for RC members is the use of fiber reinforced polymer (FRP), which aimed to resist the tensile forces in needed regions. The use of FRP can enhance flexural capacity of RC members [1, 2] but, in case of shear strengthening, there are FRP debonding problem from side of the beam [3].

Strengthening by fiber reinforced concrete (FRC) is one of interesting techniques. Addition of short discrete fibers to concrete can improve tensile strength, toughness and ductility [4-8]. Recently, fiber reinforced concrete and fiber reinforced cement composite have been used for strengthening and repair of RC structures [9, 10]. Martinola et al. [11] and Kobayashi and Rokugo [12] used high performance fiber reinforced concrete (HPFRC) to strengthen RC beams by jacketing and patching, respectively. The steel-reinforced strain hardening cementitious composites (SHCCs) was utilized for the strengthening of RC beams as reported by Hussein et al. [13]. The intervention technique by the combination of high performance fiber reinforcement cement-based composite (HPFRCC) and carbon fiber reinforced polymers (CFRP) was discussed by Ferrari et al. [14]. However, the studies are focused mainly on flexural behavior. There are some publications related to the shear strengthening of RC beams using fiber reinforced concrete. Wirojjanapirom et al. [15] introduced the use of ultra-high strength fiber reinforced concrete permanent formwork for enhancing the shear capacity of RC beams. Ruano et al. [16] used the cast-in-place FRC jacketing to strengthen RC beams. Other strengthening materials such as textile-reinforced mortar (TRMs) [17, 18], cement based fiber composite material [19] and self-compacting concrete jacketing [20] were also studied. However, on the basis of a careful literature search, the research on shear strengthening using FRC is relatively limited especially the use of FRC precast panels.

In this paper, the shear strengthening method using steel fiber reinforced concrete (SFRC) panels is introduced. SFRC panels are precast members which can prepare in advance and easily install at site. In order to verify the effectiveness of this intervention technique, experimental tests and finite element analysis of the RC beams strengthened by SFRC panels were carried out. The shear capacity of RC beams after strengthening was investigated. The experimental and finite element modelling results were compared and validated. The parametric study was expanded to include additional parameters to study the shear capacity of RC beams strengthened by SFRC precast panels.

2. Experimental Study

2.1 Experimental program

The experimental program consisted of nine rectangular RC beams. The parameters investigated were (1) steel fiber volume fraction, (2) connection types, (3) number of bolts, and (4) diameter of bolt. Table 1 summarizes the experimental cases. There is a control beam without strengthening. Eight beams were strengthened using four panels on each side of the beams at shear span. The steel fiber volume fractions of strengthening panels were 0, 1.0 and 1.5%. The connection types between RC beams and panels were epoxy and bolts with epoxy. Number of bolts used per panels was varied (i.e., 4, 6, and 8 bolts). The diameter of bolts were 10 mm and 12 mm.

Table 1 Experimental cases

Beam Name	Designation	Connection types	Fiber volume fraction (%)	Number of bolts	Diameter of bolt (mm)
Control beam	RC beam	-	-	-	-
1.5F-Epoxy	Strengthened	Epoxy	1.5	-	-
0F-8D12	Strengthened	Epoxy+Bolts	0.0	8	12
1F-8D12	Strengthened	Epoxy+Bolts	1.0	8	12
1.5F-8D12	Strengthened	Epoxy+Bolts	1.5	8	12
1.5F-4D12	Strengthened	Epoxy+Bolts	1.5	4	12
1.5F-6D12	Strengthened	Epoxy+Bolts	1.5	6	12
1.5F-6D10	Strengthened	Epoxy+Bolts	1.5	6	10
1.5F-8D10	Strengthened	Epoxy+Bolts	1.5	8	10

2.2 Test specimens

All specimens had the same cross-sectional dimensions, longitudinal reinforcement ratio and stirrup ratio. Figure 1 presents dimension and reinforcement of the RC beams. The beams were 150 mm wide, 300 m high and 1800 mm long. The shear span (*a*) was 700 mm. Effective depth (*d*) was 250 mm. Two 25-mm-diameter deformed rebars were used as the main longitudinal reinforcement, and two 6-mm-diameter round rebars were used as the top reinforcement. Shear reinforcement were 6-mm-diameter round rebars. All beams were designed to fail in shear. In order to control the side of failure, fewer stirrups were provided in the left shear span as illustrated in Fig. 1. The stirrup ratio in test span was 0.12%.

The SFRC panels were used as an external shear reinforcement. The dimension of panels was 300x700x10 mm. Four SFRC panels were attached to both sides of RC beams at shear span by epoxy adhesive, as shown in Fig. 2. Figure 3 presents the details of strengthening panels. Bolt arrangement is different depending on number of bolts per panel.

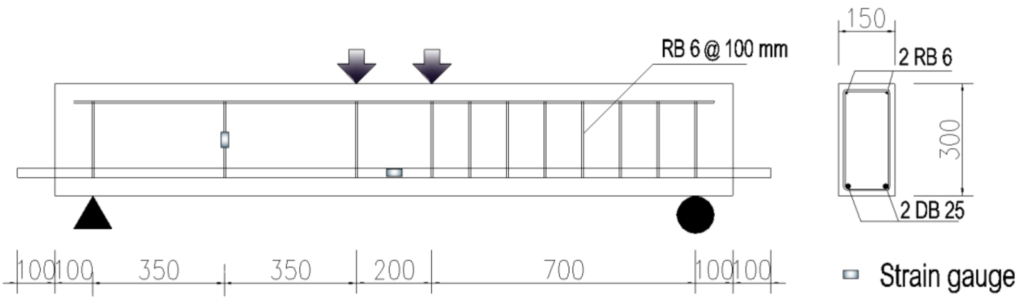


Figure 1 Geometry and reinforcement of RC beams (unit: mm)

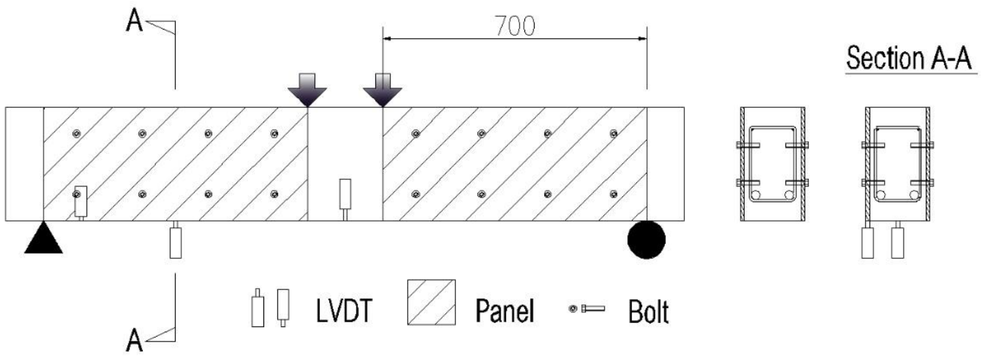
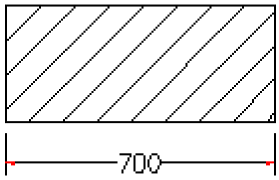
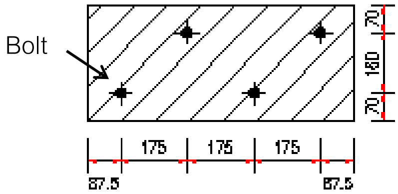


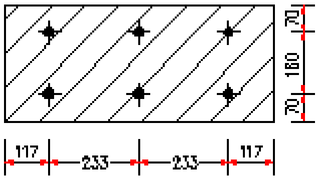
Figure 2 Details of strengthened specimens and measurement (unit: mm)



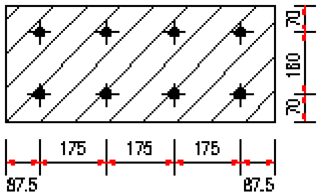
(a) No bolt



(b) 4 bolts



(c) 6 bolts



(d) 8 bolts

Figure 3 Panel geometry and bolt arrangement (unit: mm)

2.3 Materials

Ready-mixed concrete with an average cylinder compressive strength of 30 MPa was used for all beams. The mix proportion of concrete is presented in Table 2. The yield of stirrups and tensile reinforcing steel bars were 235 MPa and 502 MPa, respectively. Elastic modulus of both reinforcements is 200 GPa.

For the SFRC panels, the commercially available high strength mortar (Lanko 701) was mixed with hooked-end steel fibers. The water to powder ratio was 0.175 by weight, as suggested in the product guidelines. Table 3 lists the properties of steel fibers. The fiber volume fractions were 0%, 1.0% and 1.5%.

The panels were bonded on the beams using a two-component epoxy adhesive (Sikadur-30) with a tensile strength of 29 MPa, shear strength of 18 MPa, and elastic modulus in tension of 11.2 GPa, as given by the manufacturer. In addition, the 10 mm and 12 mm diameter chemical bolts (Anchor rod: HIT-V5.8, injection mortar: HIT-HY 200-R) were used in this study.

Table 2 Mix proportion of concrete

Water to binder ratio	Water (kg/m^3)	Cementitious materials (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Admixture (cc/m^3)	Slump (cm)
0.54	185	342	770	1,150	1,710	12.5

Table 3 Properties of steel fibers

Type	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (MPa)	*E* (GPa)	Shape of the end
Steel	35	0.55	65	1050	210	Hooked

2.4 Specimen preparation

RC beams were cast and cured for 28 days. Strengthening panels were cast with 10 mm thickness, and locations of bolts on panels were fixed by providing holes on panels in casting step. The panels were demolded after 24 hour and were cured for 7 days. Before strengthening, concrete and panel surfaces were roughened by concrete grinder and cleaned by air blower to remove dust. Then, the epoxy adhesive were applied on concrete and panel surfaces. Next, the precast panels were attached to the side of the beams. For the specimens with bolts connection, after attaching the panels, RC beams were drilled to make holes. After cleaning holes, adhesive was injected and anchor rods were finally installed.

2.5 Testing and instrumentation

All beams were tested as simply supported beams under two symmetrical point loads as shown in Fig. 2. Mid-span deflection and deflection of the panels were recorded at each load increment using linear variable displacement transducers (LVDTs). Strain of longitudinal rebar at mid-span and strain of stirrup at the middle height were measured using strain gauges. Locations of steel strain gauges are illustrated in Fig. 1. Two LVDTs were set under specimens to measure vertical displacements of RC beam and panel at the middle of shear span (Section A-A) as presented in Fig. 2.

3. Experimental Results and Discussions

3.1 Load versus deflection response at mid-span

Load-displacement responses of eight RC beams strengthened with SFRC panels were compared with control beam—RC beam without strengthening—and presented in Figs.

4 and 5. At the beginning, mid-span deflection linearly increased with applied load. Then stiffness of beams slightly decreased by initiation of flexural cracks at load level about 30 kN. Diagonal crack then initiated at the shear span resulting in the abrupt stiffness reduction of control beam (at 80 kN). It is noted that the abrupt stiffness reduction was not found in strengthened beams. Load still increased with lower stiffness until load reached to the peak. Stirrups in all beams were yielded at this stage as shown in Fig. 6. After that, load suddenly dropped and shear failure occurred in all beams. As presented in Figs. 4 and 5, all strengthened RC beams can resist higher load capacity than control beam. For most of the beams, stiffness was higher than that of control beam except the strengthened beam using epoxy connection (1.5F-Epoxy) as seen in Fig. 5.

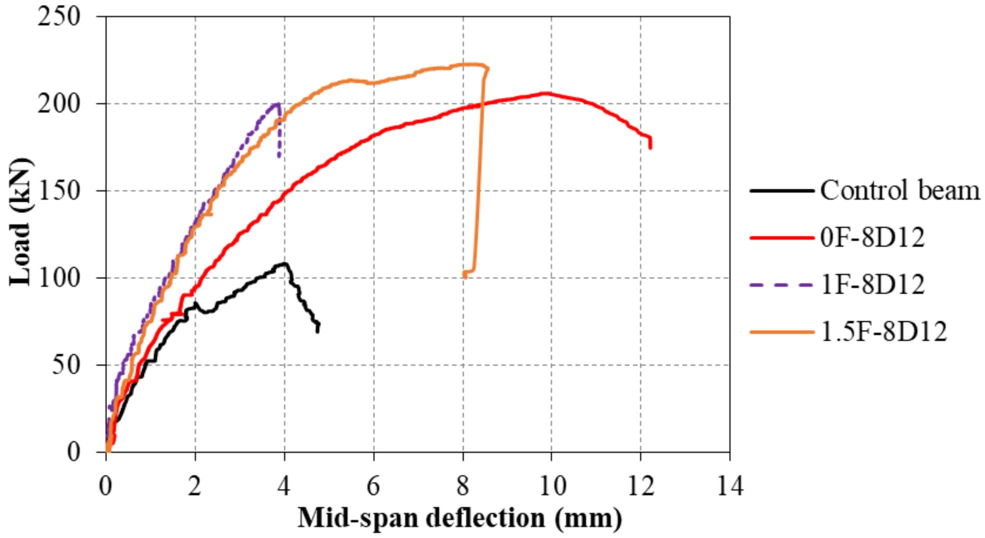


Figure 4 Load-deflection curves for beams with different steel fiber volume fraction

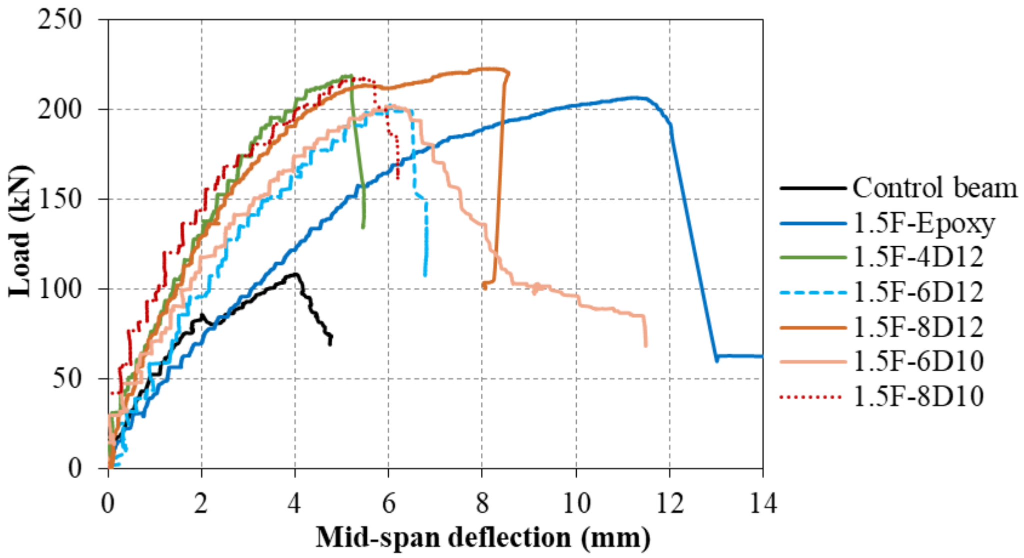


Figure 5 Load-deflection curves for beams with various connection details

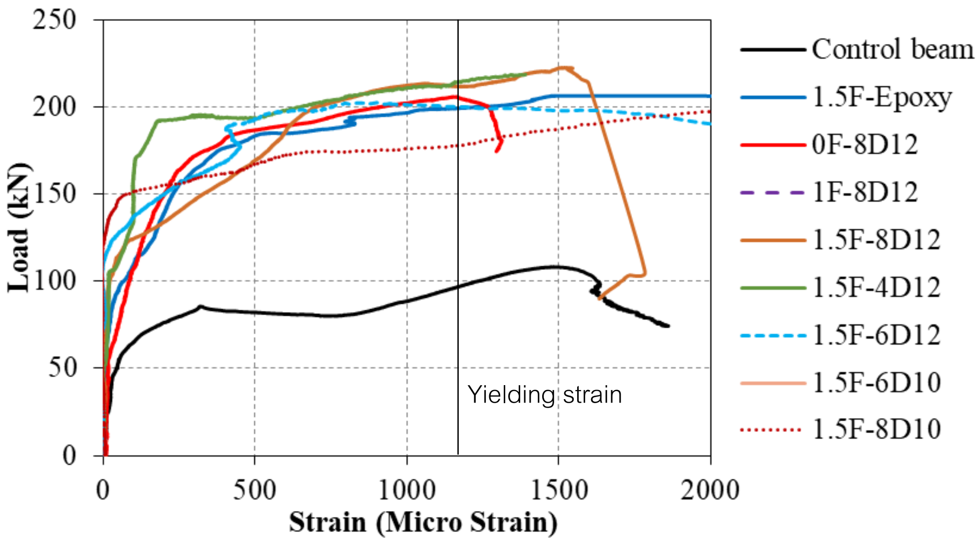


Figure 6 Load versus stirrup strain

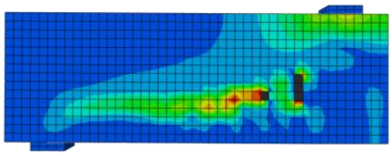
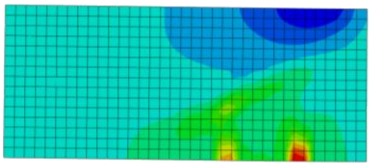
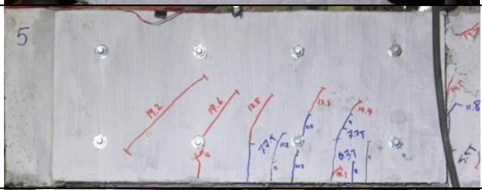
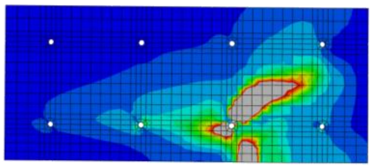
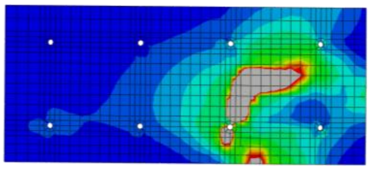
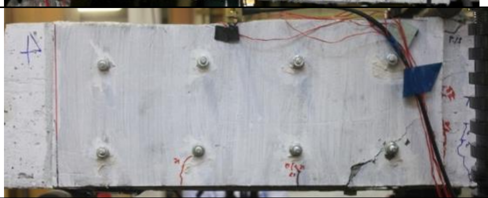
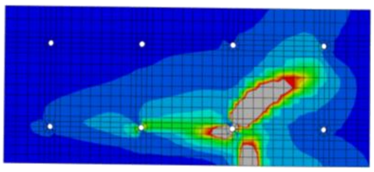
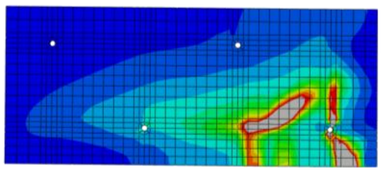
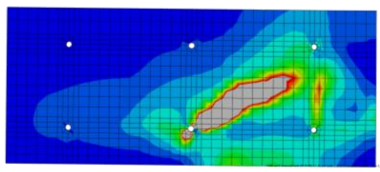
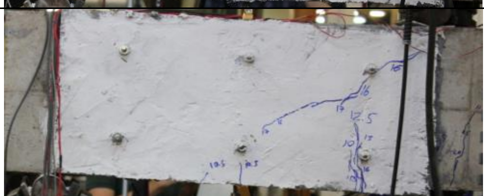
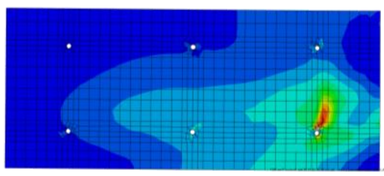
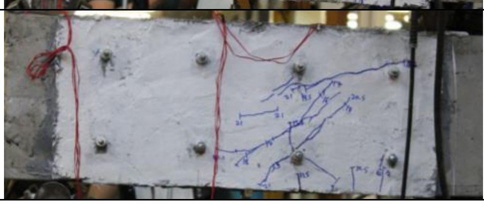
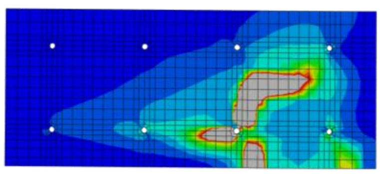
3.2 Crack pattern

Table 4 presents pictures of specimens at ultimate load. Diagonal crack was clearly seen in control beam. The diagonal crack was first observed at the middle height of beam and then propagated to support and loading point. Control beam failed when concrete compression zone crushed. Diagonal tension failure occurred in control beam.

When epoxy connection (1.5F-Epoxy) was used, no crack was observed on SFRC panels. However, at the peak load, one of SFRC panel fell off without warning and the diagonal crack was found on concrete surface.

Debonding failure was not observed in specimens with epoxy and bolt connection. All panels still attached to RC beams until test completed. A number of cracks were observed on mortar panels (0F-8D12) due to low tensile strength of mortar as shown in Table 4. Nonetheless, number of cracks on panels decreased significantly when SFRC panels were used. Only few cracks were observed on panels. Cracks initiated near bolts and normally connected between two bolts before it penetrated to loading point. Location of bolt strongly affected the diagonal crack pattern.

Table 4 Experimental and FE crack distribution

Beam	Pictures of specimens at peak load	Principal stress from FEM
Control beam		
1.5F-Epoxy		
0F-8D12		
1F-8D12		
1.5F-8D12		
1.5F-4D12		
1.5F-6D12		
1.5F-6D10		
1.5F-8D10		

3.3 Shear strengthening performance of SFRC precast panels

Table 5 summarizes compressive strength of concrete and SFRC, ultimate load capacity (P_{exp}), shear capacity from the experiment (V_{exp}) and shear enhancement ratio. Shear enhancement ratio was calculated as V_{exp} divided by shear capacity of control beam. Experimental results shows that shear capacity of beams remarkably increased 1.85-2.05 times after strengthening by SFRC panels. Effects of each parameter are discussed in the following section.

Table 5 Summary of experimental and analytical results

Beam Name	f'_c (MPa)		Experimental results			Analytical results		
	Concrete	SFRC	P_{exp} (kN)	V_{exp} (kN)	Shear enhancement ratio	P_{FEM} (kN)	V_{FEM} (kN)	V_{FEM}/V_{exp}
Control beam	32.4	-	108.4	54.2	1.00	104.1	52.1	0.96
1.5F-Epoxy	32.4	61.8	206.6	103.3	1.91	202.0	101.0	0.98
0F-8D12	32.4	56.8	206.0	103.0	1.90	207.4	103.7	1.01
1F-8D12	36.7	69.7	200.2	100.1	1.85	204.0	102.0	1.02
1.5F-8D12	32.4	60.8	222.7	111.4	2.05	218.1	109.1	0.98
1.5F-4D12	36.7	60.8	219.0	109.5	2.02	219.3	109.6	1.00
1.5F-6D12	36.7	60.8	202.8	101.4	1.87	204.0	102.0	1.01
1.5F-6D10	36.7	60.8	202.2	101.1	1.87	205.7	102.8	1.02
1.5F-8D10	36.7	60.8	217.8	108.9	2.01	204.7	102.4	0.94

3.3.1 Effect of steel fiber volume fraction

The comparison of shear capacity of four beams with different steel fiber volume fraction is illustrated in Fig. 7. The results show that shear capacity of RC beams enhanced when strengthening panels were attached. The effect of steel fiber volume fraction on shear capacity is not clear when compared 0% with 1% of fibers because shear capacity of 0F-8D12 is close to that of 1F-8D12. However, when steel fiber content increased to 1.5%, the shear capacity notably increased. Shear capacity of 1.5F-8D12 was 8% and 11% greater than shear capacity of 0F-8D12 and 1F-8D12, respectively. Moreover, as presented in Fig. 4, the increase in steel fiber volume fraction increased the stiffness of beams. Compatibility between RC beam and panels is also confirmed. Figure 8 presents relationship between load and vertical displacement measured under RC beam and panel. When mortar panels were used, vertical displacement between RC beam and the panel were different since early stage as shown in Fig. 8(a). Nevertheless, with the increase in steel fiber volume fraction, vertical displacements of beam and panel became closer as presented in Figs. 8(b) and 8(c). This may come from the reduction of number of crack in panels when steel fibers were added. In short, the increase in steel fiber volume fraction improved shear capacity and stiffness and also decreased relative displacement between panels and beams.

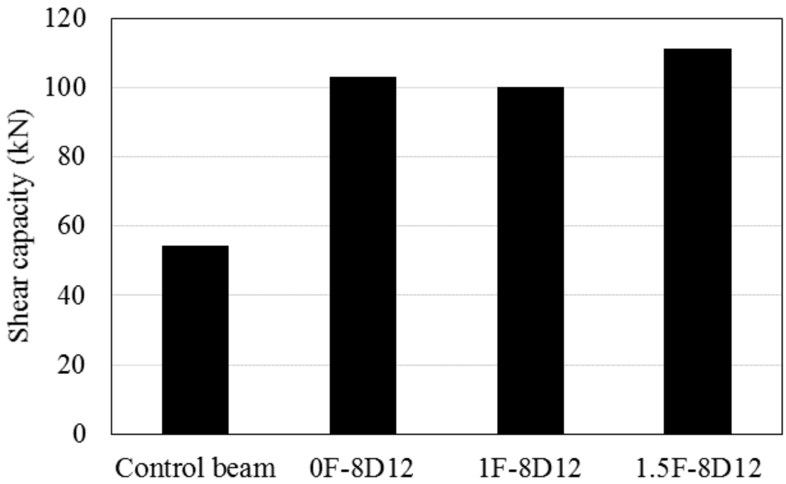
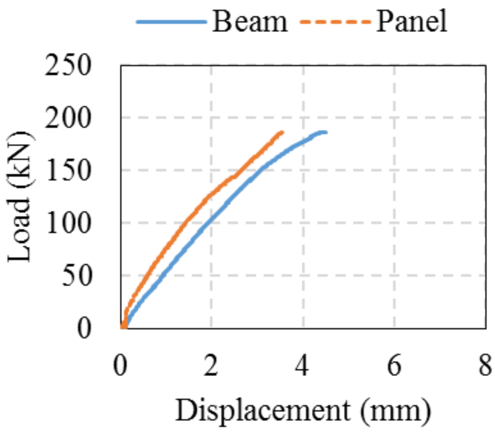


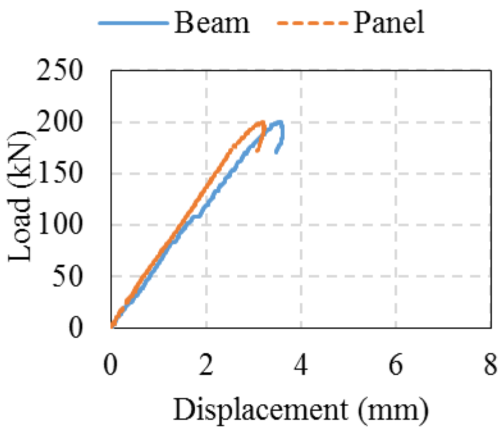
Figure 7 Shear enhancement of beams with different steel fiber volume fraction

3.3.2 Effect of connection types, number and diameter of bolts

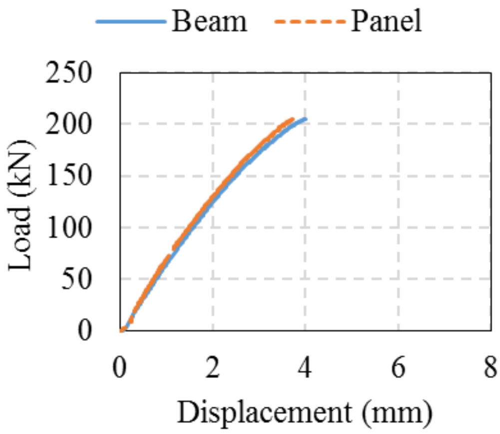
Effect of connection types is presented in Fig. 9. The shear capacity of 1.5F-Epoxy is comparable with beams with epoxy and bolt connection. However, the failure mode of specimens with epoxy connection is unsafe because 1.5F-Epoxy exhibited sudden debonding failure of SFRC panel. When epoxy-bolt connection was used, stiffness (see Fig. 5) and compatible between RC part and panel (compared Fig. 10(a) with Fig. 8(c)) significantly improved. Bolts helps to transfer shear force to panels and also prevent debonding of the panels.



(a) 0F-8D12



(b) 1F-8D12



(c) 1.5F-8D12

Figure 8 Load versus vertical displacement of RC beam and panel of specimens with different fiber volume fraction

Number of bolts per panel effects shear capacity of strengthened beams. When the number of bolts decreased from 8 to 6 bolts per panel, shear enhancement ratio reduced from 2.05 to 1.87 for 12-mm bolts and from 2.01 to 1.87 for 10-mm bolts. Nevertheless, different tendency was found when number of bolts was reduced to 4 bolts per panel. Shear enhancement ratio of 1.5F-4D12 was larger than those of 1.5F-6D12. This implies that bolt pattern strongly affects the shear capacity of strengthened beams. The relative vertical displacement between RC beams and panel at the peak load of specimens with epoxy combined with bolt connection was between 0.21-0.33 mm as presented in Figs. 8 and 10.

On the other hand, diameter of bolts did not affect shear capacity of beams because bolts did not fail. The shear capacity of 1.5F-6D10 and 1.5F-8D10 was almost equal to those of 1.5F-6D12 and 1.5F-8D12, respectively. Vertical displacements of SFRC panel and RC beams became closer when smaller bolt diameter is used as observed in in 1.5F-6D10 (Fig. 10(d)) and 1.5F-8D10 (Fig. 10(e)).

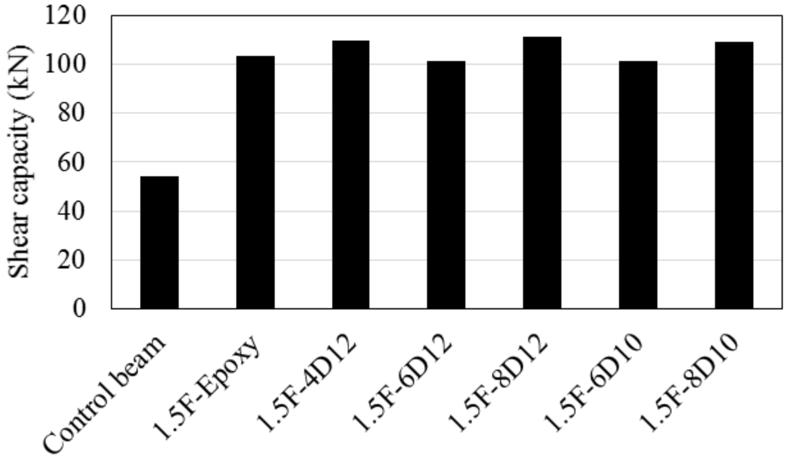
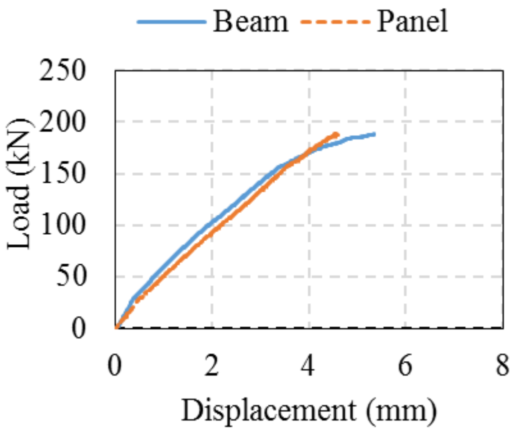
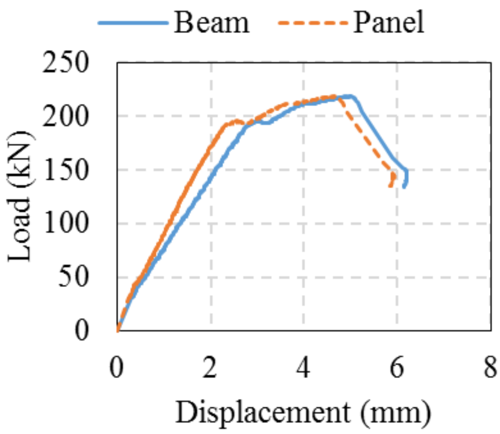


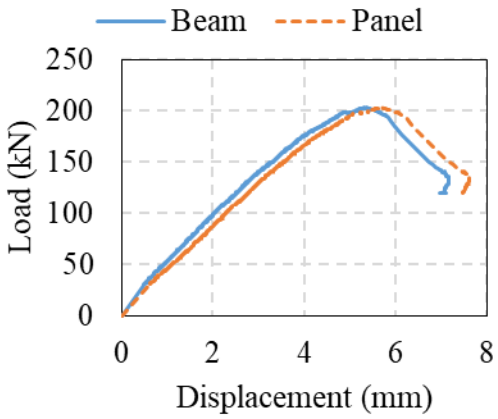
Figure 9 Shear enhancement of beams with various connection details



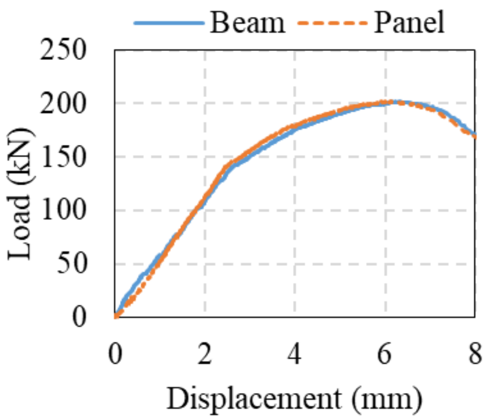
(a) 1.5F-Epoxy



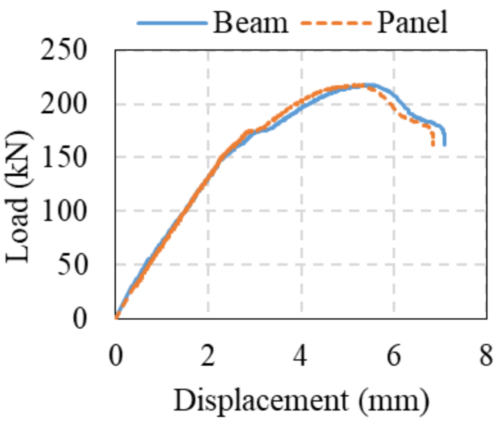
(b) 1.5F-4D12



(c) 1.5F-6D12



(d) 1.5F-6D10



(e) 1.5F-8D10

Figure 10 Load versus vertical displacement of RC beam and SFRC panel with various connection detail

4. Analysis Using Finite Element Method (FEM)

4.1 Analytical cases

Finite-element (FE) modeling of strengthened RC beams was carried out using FE software package ABAQUS. Control beam without SFRC panels was modeled first and validated with the experimental results in order to ensure capacity of program and characteristic of concrete and steel properties. Then, finite-element analysis was performed for all the specimens in experimental part and six other cases were also analyzed as parametric study. Table 6 lists the details of the beams for parametric study. Effects of panel thickness (Series I), compressive strength of SFRC (Series II), number of bolts and bolt pattern (Series III) were considered in numerical study. Geometry and bolt pattern of specimens in series I and II are same as those of 1.5F-8D12. Bolt patterns of specimens in series III are illustrated in Fig. 11.

Table 6 Details of analytical beams and results

Series	Name	SFRC panels Thickness (mm)	f_c' (MPa)	f_t (MPa)	No. of bolts	P_{FEM} (kN)	V_{FEM} (kN)	Shear enhancement ratio
I	B1	15	70	5.24	8	222.8	111.4	2.06
	B2	20	70	5.24	8	227.3	113.6	2.10
II	B3	10	50	4.95	8	202.8	101.4	1.87
	B4	10	90	6.64	8	221.4	110.7	2.04
III	B5	10	70	5.24	4	186.4	93.2	1.72
	B6	10	70	5.24	10	208.8	104.4	1.93

(a) B5 (b) B6

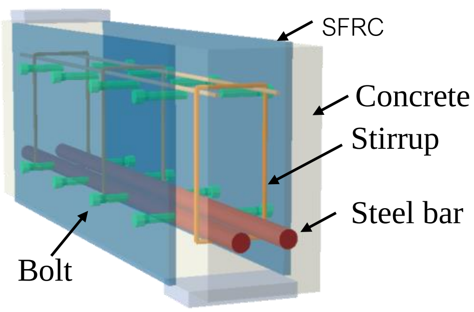
Figure 11 Bolt pattern of specimens in series III (unit: mm)

4.2 Analytical model

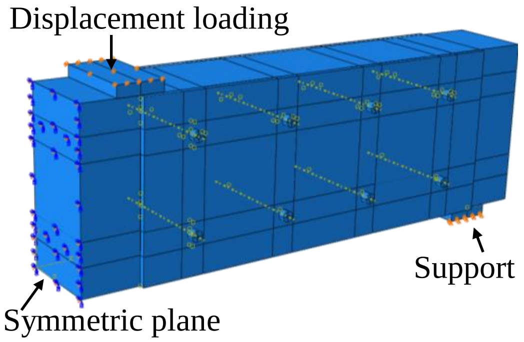
The three-dimensional (3D) FE model was developed. Due to symmetry of the beams, a half of the specimen was modeled as shown in Fig. 12(a). Concrete and SFRC elements were modeled using 8-node brick element with reduced integration (C3D8R) and 2-node truss element (T3D2) was used for steel reinforcement and stirrups. Longitudinal steel bars were embedded in concrete element at the specified location without considering the bond slip between two elements. Geometric tolerance was set to be 0.07. Bolts were modeled using 8-node brick element with reduced integration (C3D8R). Cohesive surfaces defined through the contact area were used to model the concrete-SFRC and concrete-bolt interfaces.

Mesh convergence study was carried out to examine the optimal mesh size. The results show that further decrease in the mesh size has little effect on the numerical results. Consequently, mesh size of concrete and panels was 20 mm in general and 5 mm for region near bolts as presented in Fig. 13.

Figure 12(b) shows loading and boundary condition of the model. Symmetric boundary condition was applied at the plane representing the continuous of beam. This includes the restrictions of translation along x-axis and rotation about z-axis. Roller support and loading plates were also modelled. The FE analysis was carried out with displacement control method.

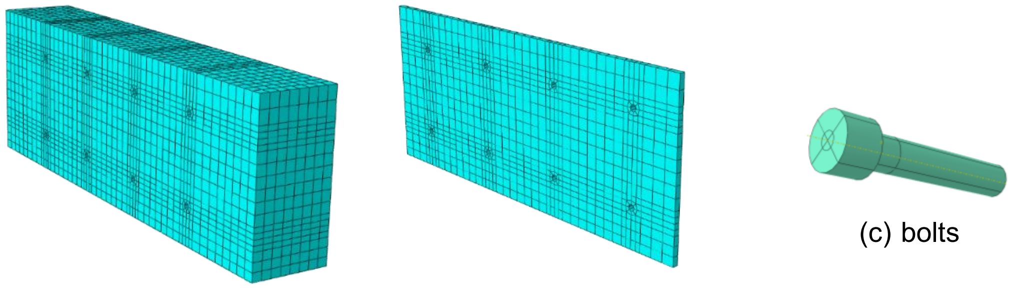


(a) FE model for 1.5F-8D12



(b) Loading and boundary condition

Figure 12 FE model



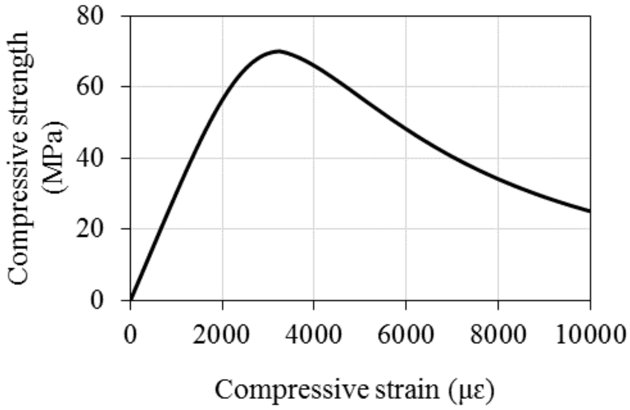
(a) Concrete (b) SFRC (c) bolts

Figure 13 FE mesh

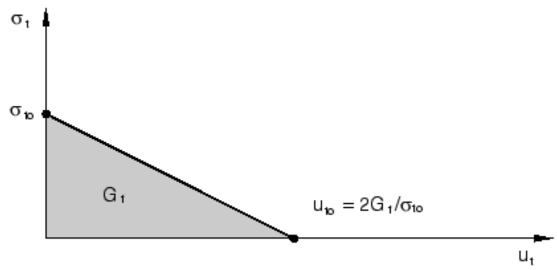
4.3 Material properties

In order to model the behavior of concrete, the concrete damage plasticity (CDP) was used. It is based on two main failure mechanisms which are tensile cracking and compressive crushing of concrete. The CDP parameters were: Poisson's ratio (0.2), the dilation angle (36°), the flow potential eccentricity (0.1), the ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress (1.16), the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian (0.667), and viscosity parameter (0.001). The stress-strain curve of concrete in compression was simulated by the model proposed by Hognestad [21] with a maximum stress equal to 32 MPa, ultimate compressive strain equal to 0.0035 and a young modulus of 27 GPa. The tensile behavior was modeled using a linear elastic branch until the tensile strength. After crack initiation, the fracture energy cracking model was adopted. The fracture energy was calculated from the equation proposed by Bazant and Becq-Giraudon [22]. The tensile strength of concrete was 3.26 MPa and the fracture energy was 1.79 N/mm.

Concrete damage plasticity was also used to simulate the behavior of steel fiber reinforced concrete. The behavior of SFRC in compression was expressed by the model proposed by Lee et al. [23] as presented in Fig. 14(a). The tensile properties of SFRC consisted of a linear elastic behavior until tensile strength and linear softening behavior after crack initiation (Fig. 14(b)). The post-failure behavior for direct straining across cracks was specified by applying a fracture energy cracking criterion, which was calculated from the equations proposed by Kovar and Foglar [24]. Compressive and tensile strengths of SFRC are listed in Table 6. Other material properties of SFRC for numerical model are: Poisson's ratio = 0.31 [25], young's modulus = 31 GPa [23], fracture energy = 4.05 N/mm, 7.30 N/mm and 8.82 N/mm for steel fiber volume fraction = 0%, 1.0% and 1.5%, respectively.



(a) Compression



(b) Post-failure stress-fracture energy curve [26]

Figure 14 Material model of SFRC

The longitudinal and shear reinforcements were modeled by a bilinear elastic-perfectly plastic model. Yield strength and young modulus were described in section 2.3. The stress–strain behavior of bolts is linear elastic material until yielding, followed by plastic behavior. The modulus of elasticity and yield stress for bolts were taken as 200 GPa and 520 MPa, respectively.

Cohesive surface was used to define the surface to surface contact between concrete-SFRC and concrete/SFRC-bolts. This model determined the potential surfaces of separation by traction-separation constitutive model as presented in Fig. 15. For the contact between concrete and SFRC, stiffness coefficient was 4600 N/mm^3 and separation at failure was 0.4 mm. Stiffness coefficient of interface between bolts and concrete/SFRC was 4000 N/mm^3 and separation at failure was 0.06 mm.

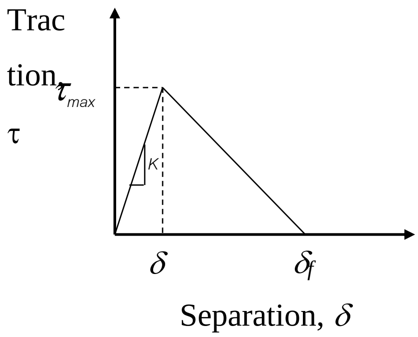
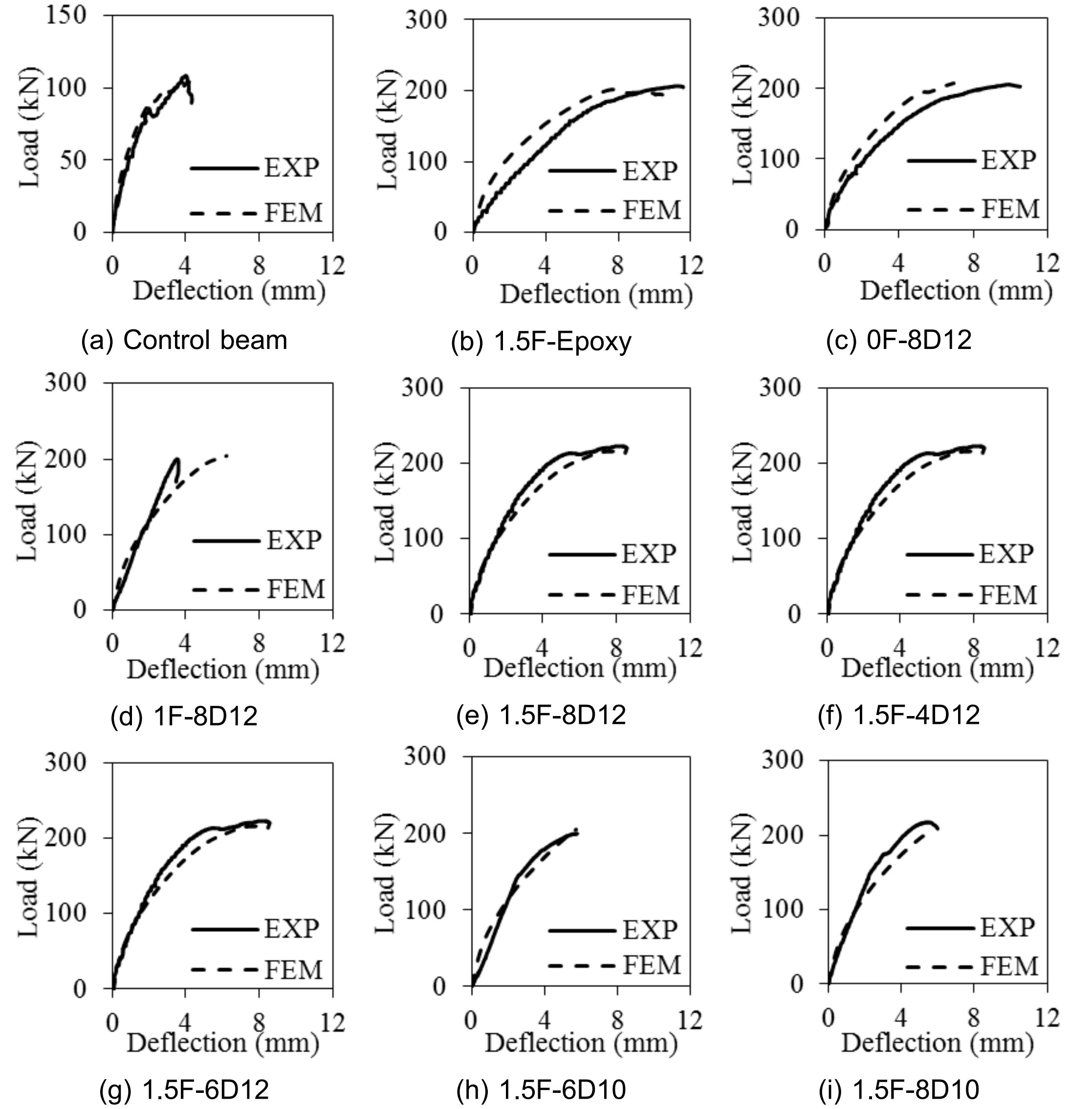


Figure 15 Traction-separation cohesive material law

4.4 Analytical results and discussions

4.4.1 Verification of the FE model

Figure 16 presents experimental and numerical comparison of the load versus mid-span deflection curves of all specimens. As seen from the figures, the experimental load-deflection curves showed good agreement especially for ultimate load capacity compared with the FE analysis of control beam and SFRC strengthening beams. Values of analytical shear capacity (V_{FEM}) are summarized in Table 5. As seen in Table 5, a maximum deviation of analytical shear capacity compared with experimental shear capacity was 6%. Crack pattern of specimens observed from experiment and FE analysis is presented in Table 4. Numerical crack pattern of control beam reveals a shear crack in shear span. For the strengthened specimens, crack patterns on SFRC panels were presented. Stress contour of 1.5F-Epoxy was different compared with results of other specimens due to debonding of SFRC panels. In other strengthened specimens, it is observed that diagonal cracks normally passed through the bolts. This behavior is also observed in the experiment. Therefore, crack patterns are reasonably captured from FE analysis. From this verification, it is proved that the FE model is appropriate to describe the shear behavior of RC beams strengthened by SFRC panels.



(a) Control beam (b) 1.5F-Epoxy (c) 0F-8D12

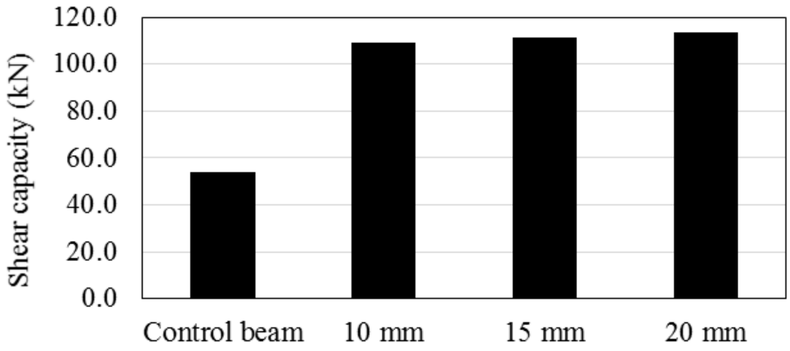
(d) 1F-8D12 (e) 1.5F-8D12 (f) 1.5F-4D12

(g) 1.5F-6D12 (h) 1.5F-6D10 (i) 1.5F-8D10

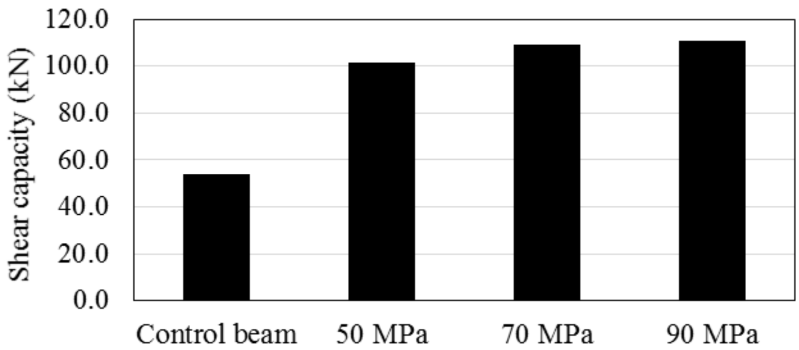
Figure 16 Load-midspan deflection comparison for tested beams

4.4.2 Parametric study

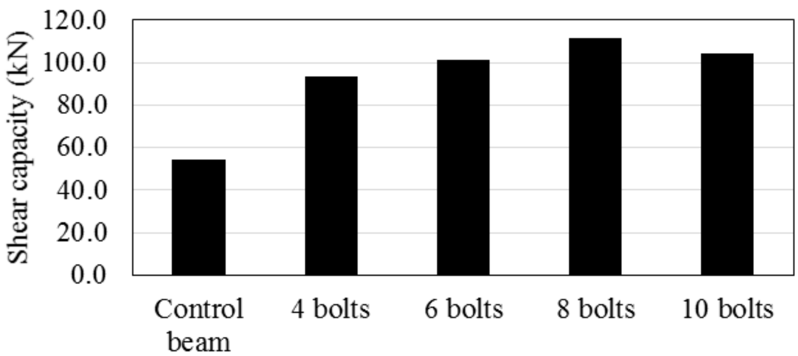
The numerical analysis was extended to determine the effects of panel thickness, compressive strength of SFRC, number of bolts and bolt pattern. Shear capacity of all analytical beams is listed in Table 5 and effects of the parameters are presented in Fig. 17. The results shows that there was an insignificant improvement of shear capacity when the thickness of panels increased from 10 mm to 15 mm and 20 mm (see Fig. 17(a)). It is because the shear contribution due to steel fibers depended on diagonal crack shape which is mainly governed by the bolt pattern. Therefore, the increase in panel thickness give relatively small contribution compared with the total shear capacity of the beams. The shear enhancement ratios of specimens with f'_{c_SFRC} = 50, 70 and 90 MPa were 1.87, 2.01, and 2.04, respectively. The shear capacity was almost the same when the compressive strength of SFRC panels exceeded 70 MPa as shown in Fig. 17(b). Figure 17(c) plots the shear capacity of beams with different number of bolt per panel. Noted that only the specimens with symmetrical bolts pattern (i.e., B5, 1.5F-6D12, 1.5F-8D12, and B6) are compared in this figure. The results show that in case of symmetrical bolts pattern the shear capacity increased when the number of bolts increased from 4 to 8 bolts. However, the shear capacity decreased when the number of bolts became 10 bolts per panel because providing many bolts per panel reduced area of SFRC panels and bolt spacing. Crack can easily connect between bolts when bolt spacing decreased as observed from crack pattern of B6 in Fig. 18(d). In the case of the smaller number of bolts, diagonal bolt pattern (1.5-4D12) gave considerably higher shear capacity than symmetrical pattern (B5) as illustrated in Fig. 17(d).



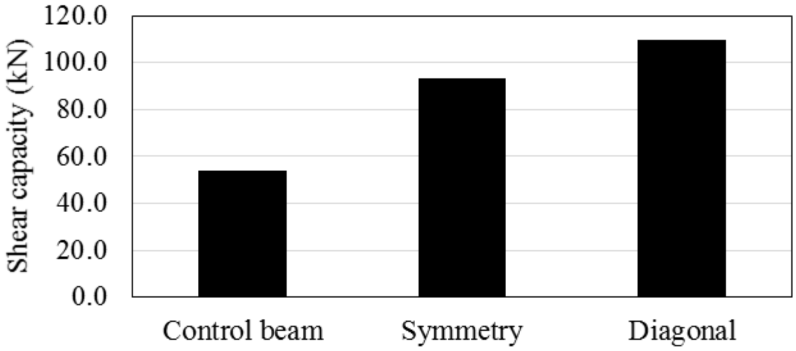
(a) Effect of panel thickness



(b) Effect of compressive strength of SFRC

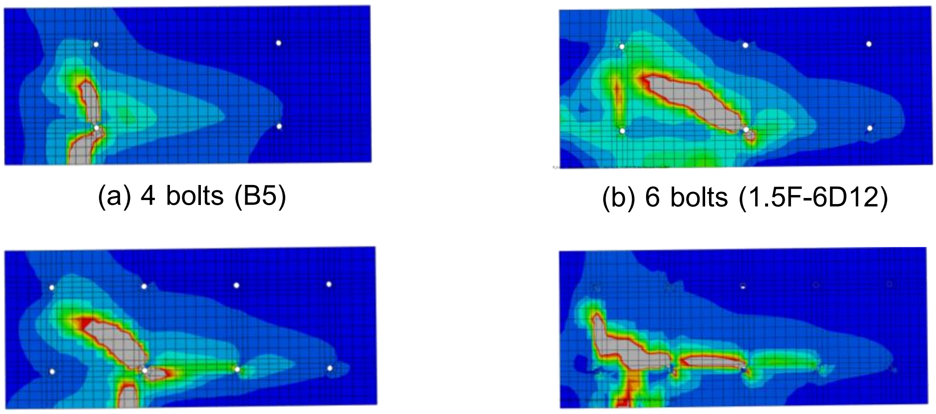


(c) Effect of number of bolts (symmetry bolt pattern case)



(d) Effect of bolt pattern

Figure 17 Results of parametric study



(a) 4 bolts (B5)

(b) 6 bolts (1.5F-6D12)

(c) 8 bolts (1.5F-8D12)

(d) 10 bolts (B6)

Figure 18 Crack pattern of the panels with different number of bolts

5. Conclusions

1. Shear capacity and beam stiffness under service load of RC beams remarkably increased when RC beams were strengthened using steel fiber reinforced concrete panels. This technique is effective to enhance the shear performance of RC beams.
2. Effect of steel fibers pronounced when the volume fraction of fiber was 1.5%. The resistance to crack of panels increased due to addition of steel fibers.
3. Shear capacity of specimens with epoxy combined with bolts connection was comparable with those of specimen with epoxy connection. However, the failure mode of the specimens was completely changed. Specimen with epoxy connection exhibited debonding failure of SFRC panel at the ultimate load and thus using only epoxy for connection is not recommended. Using epoxy combined with bolts connection can prevent debonding failure and also improve beam stiffness under service load.
4. The load-displacement relationships obtained from finite element analysis were in close agreement with the experimental results. This indicates that the presented

numerical modelling procedure can be used for predicting the shear behavior of RC beams strengthened using SFRC panels up to ultimate stage.

5. The experimental and analytical results show that the shear capacity increased with the increase in number of bolts up to 8 bolts per panel and compressive strength of SFRC up to 70 MPa. The further increase beyond these values shows another tendency. Bolts patterns strongly affected the shear behavior of the beams. Diameter of bolts and panel thickness insignificantly effected the shear capacity of strengthened beams.

References

[1] Pham, H., Al-Mahaidi, R., Experimental investigation into flexural retrofitting of reinforced concrete bridge beams using FRP composites, *Composite Structures*, Vol. 66, No. 1–4, 2004, pp. 617-625, https://doi.org/10.1016/j.compstruct.2004.05.010.

[2] Al-Saidy, A.H., Al-Harthy, A.S., Al-Jabri, K.S., Abdul-Halim, M., Al-Shidi, N.M., Structural performance of corroded RC beams repaired with CFRP sheets, *Composite Structures*, Vol. 92, No. 8, 2010, pp. 1931-1938, https://doi.org/10.1016/j.compstruct.2010.01.001.

[3] Chen, J.F., Teng, J.G., Shear capacity of FRP-strengthened RC beams: FRP debonding, *Construction and Building Materials*, Vol. 17, No., 2003, pp. 27-41, https://doi.org/10.1016/S0950-0618(02)00091-0.

[4] Balaguru, P., Narahari, R., Patel, M., Flexural toughness of steel fiber reinforced concrete, *ACI Material Journal*, Vol. 89, No. 6, 1992, pp. 541-546.

[5] Li, V.C., Ward, R., Hamaza, A.M., Steel and synthetic fibers as shear reinforcement, *ACI Materials Journal*, Vol. 89, No. 5, 1992, pp. 499-508.

[6] Wafa, F.F., Ashour, S.A., Mechanical properties of high-strength fiber reinforced concrete, *ACI Material Journal*, Vol. 89, No. 5, 1992, pp. 449-455.

[7] Bischoff, P.H., Tension stiffening and cracking of steel fiber-reinforced concrete, *Journal of Materials in Civil Engineering*, Vol. 15, No. 2, 2003, pp. 174-182.

[8] Thomas, J., Ramaswamy, A., Mechanical properties of steel fiber-reinforced concrete, *Journal of Materials in Civil Engineering*, Vol. 19, No. 5, 2007, pp. 285-392, https://doi.org/10.1061/(ASCE)0899-1561(2007)19:5(385).

[9] Meda, A., Mostosi, S., Riva, P., Shear strengthening of reinforced concrete beam with high-performance fiber-reinforced cementitious composite jacketing. *ACI Structural Journal*, Vol. 111, No. 5, 2014, pp. 1059–1067.

[10] Meda, A., Mostosi, S., Rinaldi, Z., Riva, P., Corroded RC columns repair and strengthening with high performance fiber reinforced concrete jacket. *Materials and Structures*, Vol. 49, No. 5, 2016, pp. 1967–1978, https://doi.org/10.1617/s11527-015-0627-1.

[11] Martinola, G., Meda, A., Plizzari, G.A., Rinaldi, Z., Strengthening and repair of RC beams with fiber reinforced concrete, *Cement and Concrete Composites*, Vol. 32, No. 9, 2010, pp. 731–739, https://doi.org/10.1016/j.cemconcomp.2010.07.001.

[12] Kobayashi, K., Rokugo, K., Mechanical performance of corroded RC member repaired by HPFRCC patching, *Construction and Building Materials*, Vol. 39, 2013, pp. 139-147, https://doi.org/10.1016/j.conbuildmat.2012.05.013.

[13] Hussein, M., Kunieda, M., Nakamura H., Strength and ductility of RC beams strengthened with steel-reinforced strain hardening cementitious composites, *Cement and Concrete Composites*, Vol. 34, 2012, pp. 1061-1066, https://doi.org/10.1016/j.cemconcomp.2012.06.004.

[14] Ferrari, V.J., Hanai, J.B., Souza, R.A., Flexural strengthening of reinforcement concrete beams using high performance fiber reinforcement cement-based composite (HPFRCC) and carbon fiber reinforced polymers (CFRP), *Construction and Building Materials*, Vol. 48, 2013, pp. 485-498, https://doi.org/10.1016/j.conbuildmat.2013.07.026.

[15] Wirojjanapirom, P., Matsumoto, K., Kono, K., Niwa, J., Experimental study on shear behavior of RC beams using U-shape UFC permanent formwork with shear keys and bolts. *Journal of Japan Society of Civil Engineers, Ser. E2 (Materials and Concrete Structures)*, Vol. 69, No. 1, 2013, pp. 67-81, https://doi.org/10.2208/jscejmcs.69.67.

[16] Ruano, G., Isla, F., Pedraza, R. I., Domingo, S., Luccioni, B., Shear retrofitting of reinforced concrete beams with steel fiber reinforced concrete, *Construction and Building Materials*, Vol. 54, 2014, pp. 646-658, https://doi.org/10.1016/j.conbuildmat.2013.12.092.

[17] Al-Salloum, Y.A., Elsanadedy, H.M., Alsayed, S.H., Iqbal, R.A., Experimental and numerical study for the shear strengthening of RC beams using textile reinforced mortar, *Journal of Composites for Construction*, Vol. 16, No.1, 2012, pp. 74-90, https://doi.org/10.1061/(ASCE)CC.1943-5614.0000239.

[18] Escrig, C., Gil, L., Bernat-Maso, E., Puigvert, F., Experimental and analytical study of reinforced concrete beams shear strengthened with different types of textile-

reinforced mortar, *Construction and Building Materials*, Vol. 83, 2015, pp. 248-260, https://doi.org/10.1016/j.conbuildmat.2015.03.013.

[19] Ombres, L., Structural performances of reinforced concrete beams strengthened in shear with a cement based fiber composite material, *Composite Structures*, Vol. 122, 2015, pp. 316-329, https://doi.org/10.1016/j.compstruct.2014.11.059.

[20] Chalioris, C.E., Thermou, G.E., Pantazopoulou, S.J., Behaviour of rehabilitated RC beams with self-compacting concrete jacketing – Analytical model and test results, *Construction and Building Materials*, Vol. 55, 2014, pp. 257-273, https://doi.org/10.1016/j.conbuildmat.2014.01.031.

[21] Hognestad, E., Study of combined bending and axial load in reinforced concrete members, University of Illinois at Urbana Champaign, College of Engineering. Engineering Experiment Station, 1951.

[22] Bažant, Z.P., Becq-Giraudon, E., Statistical prediction of fracture parameters of concrete and implications for choice of testing standard. *Cement and Concrete Research*, Vol. 32, No. 4, 2002, pp. 529-55, https://doi.org/10.1016/S0008-8846(01)00723-2

[23] Lee, S.C., Oh, J.H., Cho, J.Y., Compressive behavior of fiber-reinforced concrete with end-hooked steel fibers. *Materials,* Vol. 8, No. 4, 2015, pp. 1442-1458, https://doi.org/10.3390/ma8041442

[24] Kovar, M., Foglar, M., An analytical description of the force–deflection diagram of FRC. *Composites Part B: Engineering*, Vol. 69, 2015, pp. 550-561, https://doi.org/10.1016/j.compositesb.2014.10.021

[25] Padmarajaiah, S. K., Influence of fibers on the behavior of high strength concrete in fully/partially prestressed beams: an experimental and analytical study. Ph.D. thesis, Indian Institute of Science, Bangalore, India, 1999.

[26] ABAQUS documentation, ABAQUS 2016, USA: Hibbitt, Karlsson and Sorensen; 2015.

ภาคผนวก

1. ผลงานตีพิมพ์ในวารสารวิชาการนานาชาติ
   - Jongvivatsakul, P., Koyekaewphring, T., and Stitmannaithum, B., “Shear strengthening of reinforced concrete beams with steel fiber reinforced concrete panels”, Construction and Building Materials, 2018. (Preparing for submission)

2. อื่นๆ (Proceeding)
   - Jongvivatsakul, P., Kunawisarut, A., Poolsu, S and Stitmannaithum B. (2016) “Comparisons of Connection Types on Shear Capacity of RC Beams Strengthened by Steel Fiber Reinforced Concrete Panels”, Proceeding of the Fourteenth East Asia – Pacific Conference on Structural Engineering and Construction (EASEC-14), pp. 1671-1678, January 6-8, 2016, Ho Chi Minh City, Vietnam.

Shear strengthening of reinforced concrete beams with steel fiber reinforced concrete panels

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Abstract

Shear performance of reinforced concrete beams strengthened with steel fiber reinforced concrete (SFRC) panels was investigated by experiment and numerical analysis. SFRC precast panels were attached to side of RC beams in order to enhance shear capacity of the beams. Series of RC beams strengthened by SFRC panels were tested under four point loading test to determine effects of fiber volume fraction, connection type, number and diameter of bolts. A three-dimensional nonlinear finite element analysis was also conducted in order to obtain a better understanding of shear behavior of strengthened RC beams. Good agreement was achieved between the experimental and analytical results especially for the ultimate load of RC beams. In addition, parametric study was performed to investigate effects of panel thickness, compressive strength of SFRC, and bolt pattern. The experimental and numerical results show that shear capacity of RC beams significantly increased after strengthening by SFRC panels. As a result, strengthening by SFRC precast panels is one of efficient techniques to improve shear capacity of RC beams.

Keywords: Fiber reinforced concrete; Shear; Strengthening; Experiment; Finite element analysis

1. Introduction

The deterioration of reinforced concrete (RC) structures has increased nowadays due to the degradation of structural materials, the increase in design load or suffer from disaster. However, only few RC structures have been strengthened or repaired. In the near future, a number of RC members requiring for strengthening or repair are going to increase significantly. In order to prepare for upcoming-retrofitting era, it is important to develop the strengthening and repair techniques as well as to investigate the load carrying capacity of RC members after strengthening in order to ensure safety of structures.

One of the common strengthening techniques for RC members is the use of fiber reinforced polymer (FRP), which aimed to resist the tensile forces in needed regions. The use of FRP can enhance flexural capacity of RC members [1, 2] but, in case of shear strengthening, there are FRP debonding problem from side of the beam [3].

Strengthening by fiber reinforced concrete (FRC) is one of interesting techniques. Addition of short discrete fibers to concrete can improve tensile strength, toughness and ductility [4-8]. Recently, fiber reinforced concrete and fiber reinforced cement composite have been used for strengthening and repair of RC structures [9, 10]. Martinola et al. [11] and Kobayashi and Rokugo [12] used high performance fiber reinforced concrete (HPFRC) to strengthen RC beams by jacketing and patching, respectively. The steel-reinforced strain hardening cementitious composites (SHCCs) was utilized for the strengthening of RC beams as reported by Hussein et al. [13]. The intervention technique by the combination of high performance fiber reinforcement cement-based composite (HPFRCC) and carbon fiber reinforced polymers (CFRP) was discussed by Ferrari et al. [14]. However, the studies are focused mainly on flexural behavior. There are some publications related to the shear strengthening of RC beams using fiber reinforced concrete. Wirojjanapirom et al. [15] introduced the use of ultra-high strength fiber reinforced concrete permanent formwork for enhancing the shear capacity of RC beams. Ruano et al. [16] used the cast-in-place FRC jacketing to strengthen RC beams. Other strengthening materials such as textile-reinforced mortar (TRMs) [17, 18], cement based fiber composite material [19] and self-compacting concrete jacketing [20] were also studied. However, on the basis of a careful literature search, the research on shear strengthening using FRC is relatively limited especially the use of FRC precast panels.

In this paper, the shear strengthening method using steel fiber reinforced concrete (SFRC) panels is introduced. SFRC panels are precast members which can prepare in advance and easily install at site. In order to verify the effectiveness of this intervention technique, experimental tests and finite element analysis of the RC beams strengthened by SFRC panels were carried out. The shear capacity of RC beams after strengthening was investigated. The experimental and finite element modelling results were compared and validated. The parametric study was expanded to include additional parameters to study the shear capacity of RC beams strengthened by SFRC precast panels.

2. Experimental Study

2.1 Experimental program

The experimental program consisted of nine rectangular RC beams. The parameters investigated were (1) steel fiber volume fraction, (2) connection types, (3) number of bolts, and (4) diameter of bolt. Table 1 summarizes the experimental cases. There is a control beam without strengthening. Eight beams were strengthened using four panels on each side of the beams at shear span. The steel fiber volume fractions of strengthening panels were 0, 1.0 and 1.5%. The connection types between RC beams and panels were epoxy and bolts with epoxy. Number of bolts used per panels was varied (i.e., 4, 6, and 8 bolts). The diameter of bolts were 10 mm and 12 mm.

Table 1 Experimental cases

Beam Name	Designation	Connection types	Fiber volume fraction (%)	Number of bolts	Diameter of bolt (mm)
Control beam	RC beam	-	-	-	-
1.5F-Epoxy	Strengthened	Epoxy	1.5	-	-
0F-8D12	Strengthened	Epoxy+Bolts	0.0	8	12
1F-8D12	Strengthened	Epoxy+Bolts	1.0	8	12
1.5F-8D12	Strengthened	Epoxy+Bolts	1.5	8	12
1.5F-4D12	Strengthened	Epoxy+Bolts	1.5	4	12
1.5F-6D12	Strengthened	Epoxy+Bolts	1.5	6	12
1.5F-6D10	Strengthened	Epoxy+Bolts	1.5	6	10
1.5F-8D10	Strengthened	Epoxy+Bolts	1.5	8	10

2.2 Test specimens

All specimens had the same cross-sectional dimensions, longitudinal reinforcement ratio and stirrup ratio. Figure 1 presents dimension and reinforcement of the RC beams. The beams were 150 mm wide, 300 m high and 1800 mm long. The shear span (*a*) was 700 mm. Effective depth (*d*) was 250 mm. Two 25-mm-diameter deformed rebars were used as the main longitudinal reinforcement, and two 6-mm-diameter round rebars were used as the top reinforcement. Shear reinforcement were 6-mm-diameter round rebars. All beams were designed to fail in shear. In order to control the side of failure, fewer stirrups were provided in the left shear span as illustrated in Fig. 1. The stirrup ratio in test span was 0.12%.

The SFRC panels were used as an external shear reinforcement. The dimension of panels was 300x700x10 mm. Four SFRC panels were attached to both sides of RC beams at shear span by epoxy adhesive, as shown in Fig. 2. Figure 3 presents the details of strengthening panels. Bolt arrangement is different depending on number of bolts per panel.

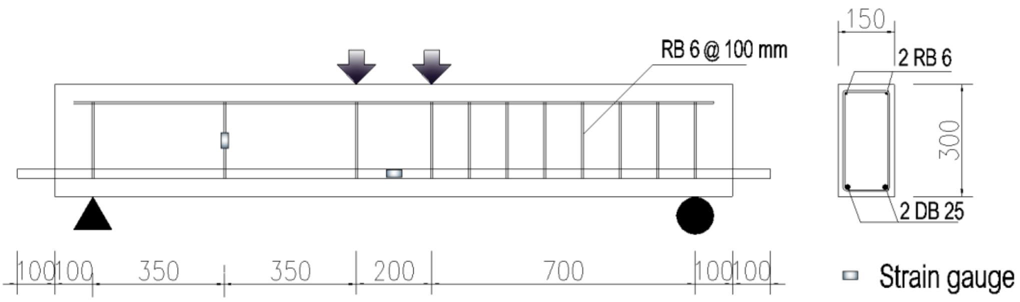


Figure 1 Geometry and reinforcement of RC beams (unit: mm)

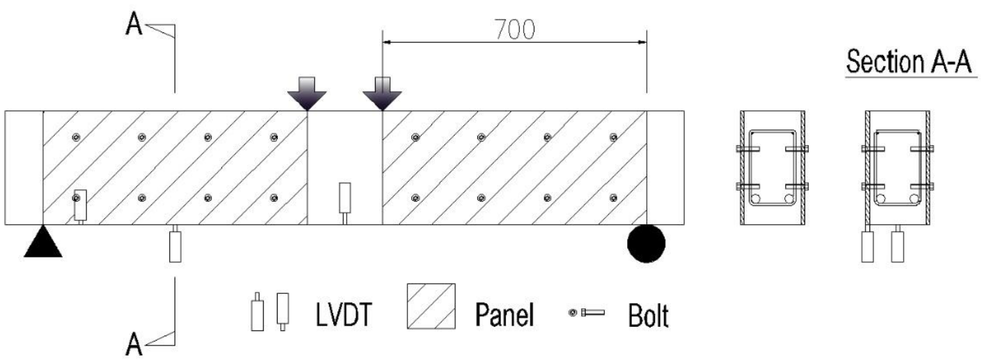
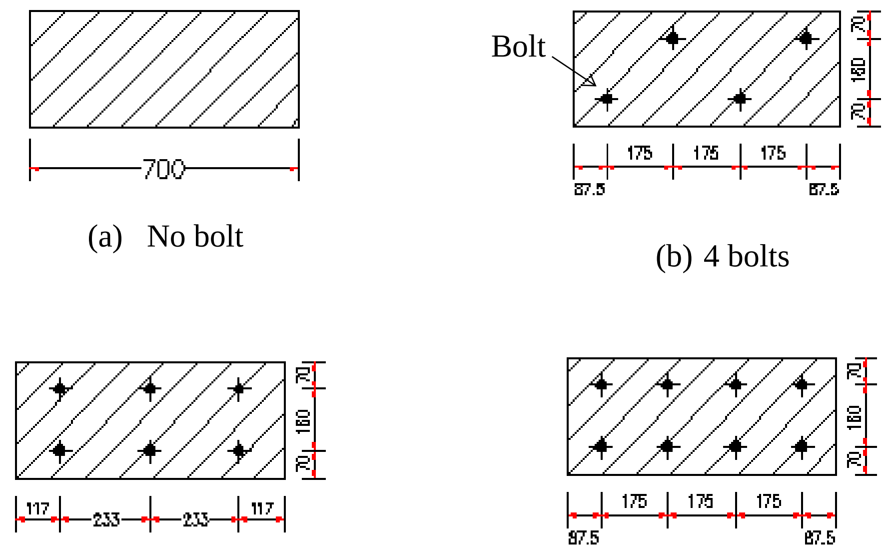


Figure 2 Details of strengthened specimens and measurement (unit: mm)



(a) No bolt (b) 4 bolts (c) 6 bolts (d) 8 bolts

Figure 3 Panel geometry and bolt arrangement (unit: mm)

2.3 Materials

Ready-mixed concrete with an average cylinder compressive strength of 30 MPa was used for all beams. The mix proportion of concrete is presented in Table 2. The yield of stirrups and tensile reinforcing steel bars were 235 MPa and 502 MPa, respectively. Elastic modulus of both reinforcements is 200 GPa.

For the SFRC panels, the commercially available high strength mortar (Lanko 701) was mixed with hooked-end steel fibers. The water to powder ratio was 0.175 by weight, as suggested in the product guidelines. Table 3 lists the properties of steel fibers. The fiber volume fractions were 0%, 1.0% and 1.5%.

The panels were bonded on the beams using a two-component epoxy adhesive (Sikadur-30) with a tensile strength of 29 MPa, shear strength of 18 MPa, and elastic modulus in tension of 11.2 GPa, as given by the manufacturer. In addition, the 10 mm and 12 mm diameter chemical bolts (Anchor rod: HIT-V5.8, injection mortar: HIT-HY 200-R) were used in this study.

Table 2 Mix proportion of concrete

Water to binder ratio	Water (kg/m^3)	Cementitious materials (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Admixture (cc/m^3)	Slump (cm)
0.54	185	342	770	1,150	1,710	12.5

Table 3 Properties of steel fibers

Type	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (MPa)	*E* (GPa)	Shape of the end
Steel	35	0.55	65	1050	210	Hooked

2.4 Specimen preparation

RC beams were cast and cured for 28 days. Strengthening panels were cast with 10 mm thickness, and locations of bolts on panels were fixed by providing holes on panels in casting step. The panels were demolded after 24 hour and were cured for 7 days. Before strengthening, concrete and panel surfaces were roughened by concrete grinder and cleaned by air blower to remove dust. Then, the epoxy adhesive were applied on concrete and panel surfaces. Next, the precast panels were attached to the side of the beams. For the specimens with bolts connection, after attaching the panels, RC beams were drilled to make holes. After cleaning holes, adhesive was injected and anchor rods were finally installed.

2.5 Testing and instrumentation

All beams were tested as simply supported beams under two symmetrical point loads as shown in Fig. 2. Mid-span deflection and deflection of the panels were recorded at each load increment using linear variable displacement transducers (LVDTs). Strain of longitudinal rebar at mid-span and strain of stirrup at the middle height were measured using strain gauges. Locations of steel strain gauges are illustrated in Fig. 1. Two LVDTs were set under specimens to measure vertical displacements of RC beam and panel at the middle of shear span (Section A-A) as presented in Fig. 2.

3. Experimental Results and Discussions

3.1 Load versus deflection response at mid-span

Load-displacement responses of eight RC beams strengthened with SFRC panels were compared with control beam—RC beam without strengthening—and presented in Figs. 4 and 5. At the beginning, mid-span deflection linearly increased with applied load. Then stiffness of beams slightly decreased by initiation of flexural cracks at load level about 30 kN. Diagonal crack then initiated at the shear span resulting in the abrupt stiffness reduction of control beam (at 80 kN). It is noted that the abrupt stiffness reduction was not found in strengthened beams. Load still increased with lower stiffness until load reached to the peak. Stirrups in all beams were yielded at this stage as shown in Fig. 6. After that, load suddenly dropped and shear failure occurred in all beams. As presented in Figs. 4 and 5, all strengthened RC beams can resist higher load capacity than control beam. For most of the beams, stiffness was higher than that of control beam except the strengthened beam using epoxy connection (1.5F-Epoxy) as seen in Fig. 5.

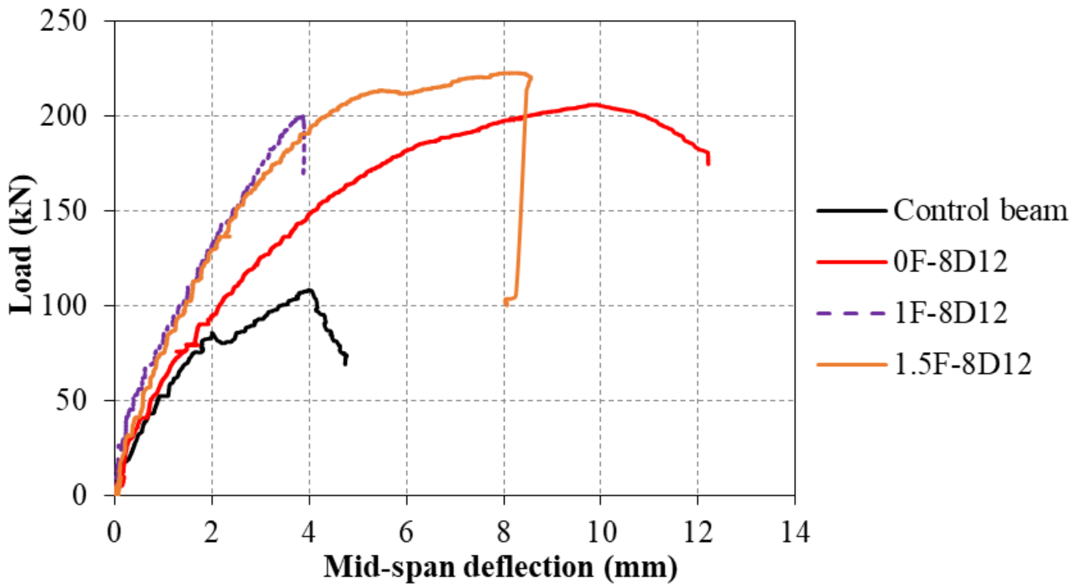


Figure 4 Load-deflection curves for beams with different steel fiber volume fraction

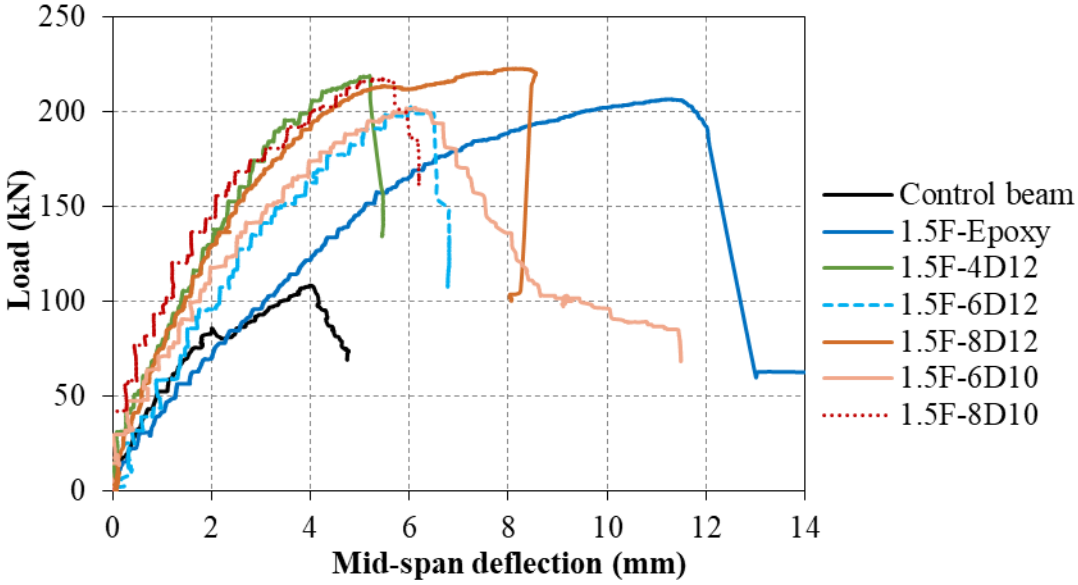


Figure 5 Load-deflection curves for beams with various connection details

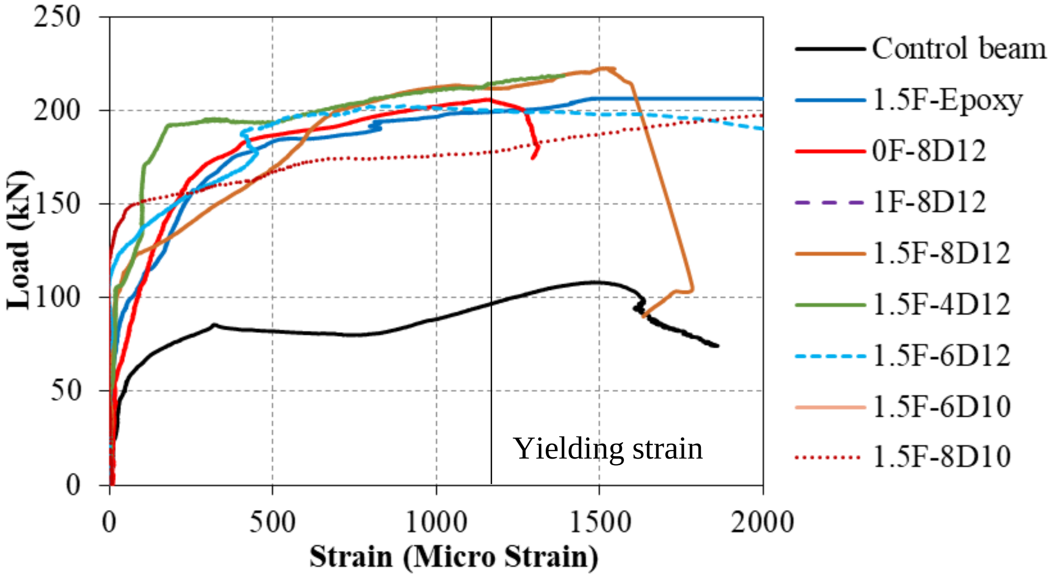


Figure 6 Load versus stirrup strain

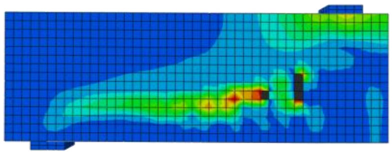
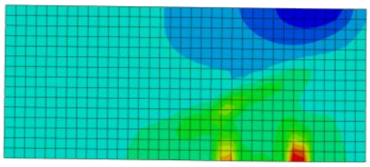
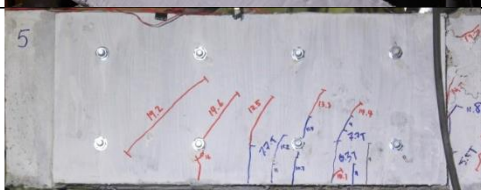
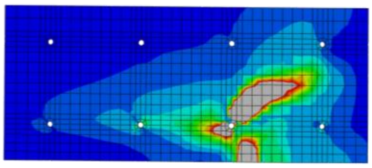
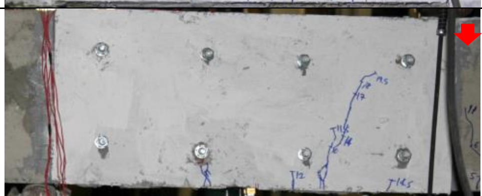
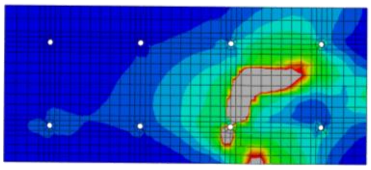
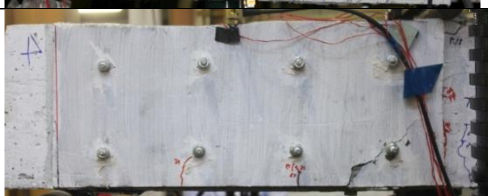
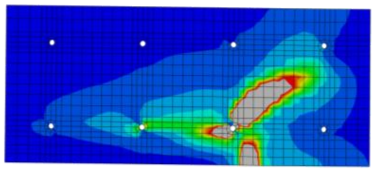
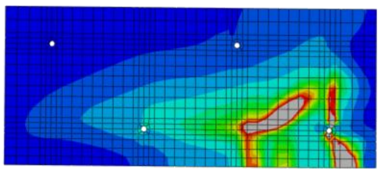
3.2 Crack pattern

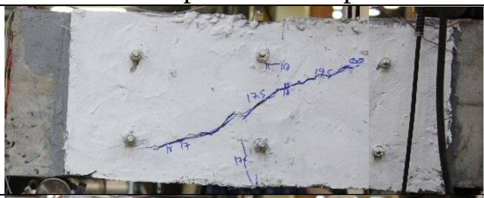
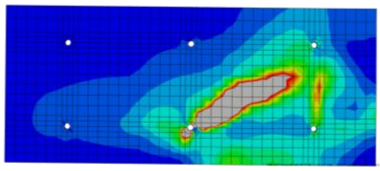
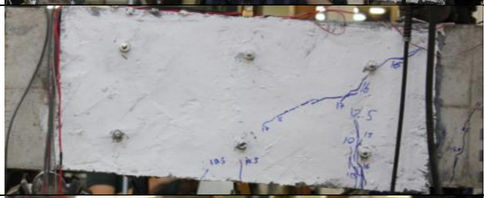
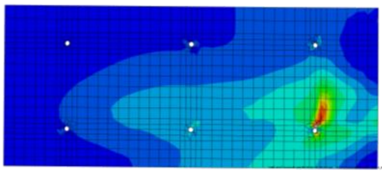
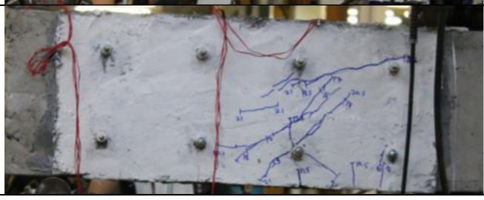
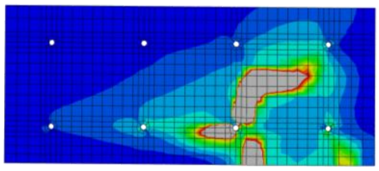
Table 4 presents pictures of specimens at ultimate load. Diagonal crack was clearly seen in control beam. The diagonal crack was first observed at the middle height of beam and then propagated to support and loading point. Control beam failed when concrete compression zone crushed. Diagonal tension failure occurred in control beam.

When epoxy connection (1.5F-Epoxy) was used, no crack was observed on SFRC panels. However, at the peak load, one of SFRC panel fell off without warning and the diagonal crack was found on concrete surface.

Debonding failure was not observed in specimens with epoxy and bolt connection. All panels still attached to RC beams until test completed. A number of cracks were observed on mortar panels (0F-8D12) due to low tensile strength of mortar as shown in Table 4. Nonetheless, number of cracks on panels decreased significantly when SFRC panels were used. Only few cracks were observed on panels. Cracks initiated near bolts and normally connected between two bolts before it penetrated to loading point. Location of bolt strongly affected the diagonal crack pattern.

Table 4 Experimental and FE crack distribution

Beam	Pictures of specimens at peak load	Principal stress from FEM
Control beam		
1.5F-Epoxy		
0F-8D12		
1F-8D12		
1.5F-8D12		
1.5F-4D12		

Beam	Pictures of specimens at peak load	Principal stress from FEM
1.5F-6D12		
1.5F-6D10		
1.5F-8D10		

3.3 Shear strengthening performance of SFRC precast panels

Table 5 summarizes compressive strength of concrete and SFRC, ultimate load capacity (P_{exp}), shear capacity from the experiment (V_{exp}) and shear enhancement ratio. Shear enhancement ratio was calculated as V_{exp} divided by shear capacity of control beam. Experimental results shows that shear capacity of beams remarkably increased 1.85-2.05 times after strengthening by SFRC panels. Effects of each parameter are discussed in the following section.

Table 5 Summary of experimental and analytical results

Beam Name	f'_c (MPa)		Experimental results			Analytical results		
	Concrete	SFRC	P_{exp} (kN)	V_{exp} (kN)	Shear enhancement ratio	P_{FEM} (kN)	V_{FEM} (kN)	V_{FEM}/V_{exp}
Control beam	32.4	-	108.4	54.2	1.00	104.1	52.1	0.96
1.5F-Epoxy	32.4	61.8	206.6	103.3	1.91	202.0	101.0	0.98
0F-8D12	32.4	56.8	206.0	103.0	1.90	207.4	103.7	1.01
1F-8D12	36.7	69.7	200.2	100.1	1.85	204.0	102.0	1.02
1.5F-8D12	32.4	60.8	222.7	111.4	2.05	218.1	109.1	0.98
1.5F-4D12	36.7	60.8	219.0	109.5	2.02	219.3	109.6	1.00
1.5F-6D12	36.7	60.8	202.8	101.4	1.87	204.0	102.0	1.01
1.5F-6D10	36.7	60.8	202.2	101.1	1.87	205.7	102.8	1.02
1.5F-8D10	36.7	60.8	217.8	108.9	2.01	204.7	102.4	0.94

3.3.1 Effect of steel fiber volume fraction

The comparison of shear capacity of four beams with different steel fiber volume fraction is illustrated in Fig. 7. The results show that shear capacity of RC beams enhanced when strengthening panels were attached. The effect of steel fiber volume fraction on shear capacity is not clear when compared 0% with 1% of fibers because shear capacity of 0F-8D12 is close to that of 1F-8D12. However, when steel fiber content increased to 1.5%, the shear capacity notably increased. Shear capacity of 1.5F-8D12 was 8% and 11% greater than shear capacity of 0F-8D12 and 1F-8D12, respectively. Moreover, as presented in Fig. 4, the increase in steel fiber volume fraction increased the stiffness of beams. Compatibility between RC beam and panels is also confirmed. Figure 8 presents relationship between load and vertical displacement measured under RC beam and panel. When mortar panels were used, vertical displacement between RC beam and the panel were different since early stage as shown in Fig. 8(a). Nevertheless, with the increase in steel fiber volume fraction, vertical displacements of beam and panel became closer as presented in Figs. 8(b) and 8(c). This may come from the reduction of number of crack in panels when steel fibers were added. In short, the increase in steel fiber volume fraction improved shear capacity and stiffness and also decreased relative displacement between panels and beams.

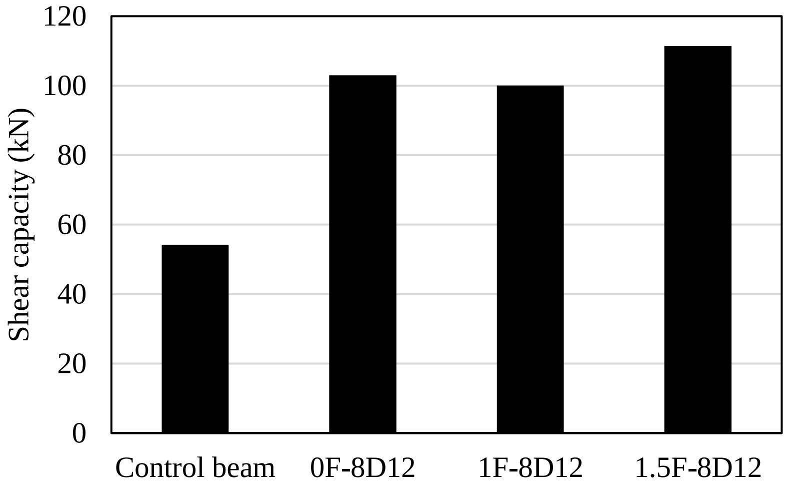
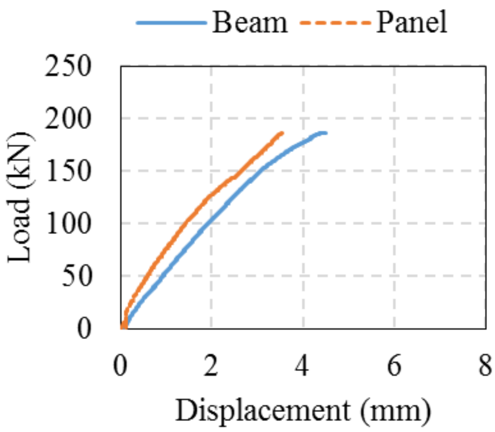
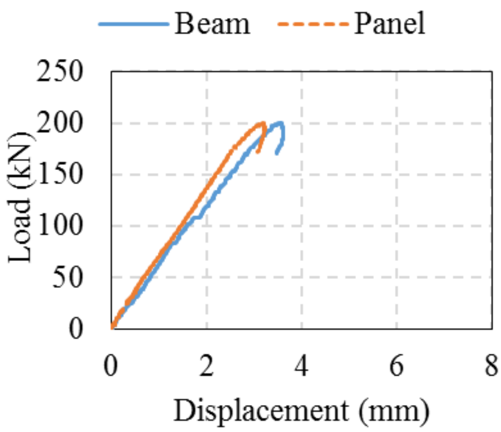


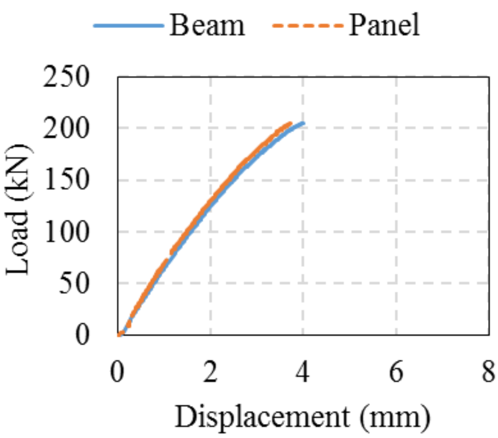
Figure 7 Shear enhancement of beams with different steel fiber volume fraction



(a) 0F-8D12



(b) 1F-8D12



(c) 1.5F-8D12

Figure 8 Load versus vertical displacement of RC beam and panel of specimens with different fiber volume fraction

3.3.2 Effect of connection types, number and diameter of bolts

Effect of connection types is presented in Fig. 9. The shear capacity of 1.5F-Epoxy is comparable with beams with epoxy and bolt connection. However, the failure mode of specimens with epoxy connection is unsafe because 1.5F-Epoxy exhibited sudden debonding failure of SFRC panel. When epoxy-bolt connection was used, stiffness (see Fig. 5) and compatible between RC part and panel (compared Fig. 10(a) with Fig. 8(c)) significantly improved. Bolts helps to transfer shear force to panels and also prevent debonding of the panels.

Number of bolts per panel effects shear capacity of strengthened beams. When the number of bolts decreased from 8 to 6 bolts per panel, shear enhancement ratio reduced from 2.05 to 1.87 for 12-mm bolts and from 2.01 to 1.87 for 10-mm bolts. Nevertheless, different tendency was found when number of bolts was reduced to 4 bolts per panel. Shear enhancement ratio of 1.5F-4D12 was larger than those of 1.5F-6D12. This implies that bolt pattern strongly affects the shear capacity of strengthened beams. The relative vertical displacement between RC beams and panel at the peak load of specimens with epoxy combined with bolt connection was between 0.21-0.33 mm as presented in Figs. 8 and 10.

On the other hand, diameter of bolts did not affect shear capacity of beams because bolts did not fail. The shear capacity of 1.5F-6D10 and 1.5F-8D10 was almost equal to those of 1.5F-6D12 and 1.5F-8D12, respectively. Vertical displacements of SFRC panel and RC beams became closer when smaller bolt diameter is used as observed in in 1.5F-6D10 (Fig. 10(d)) and 1.5F-8D10 (Fig. 10(e)).

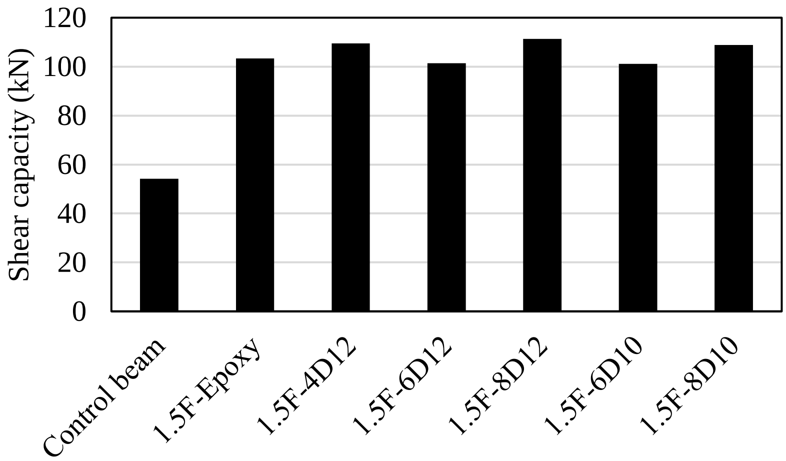
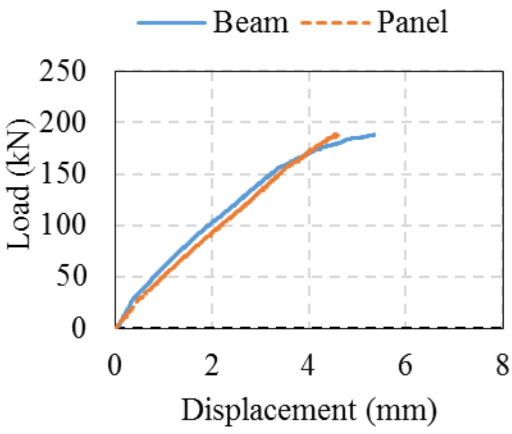
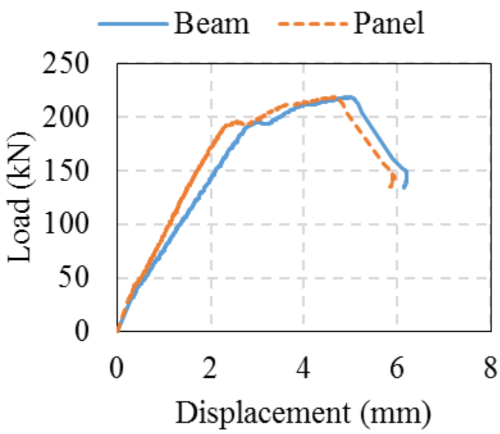


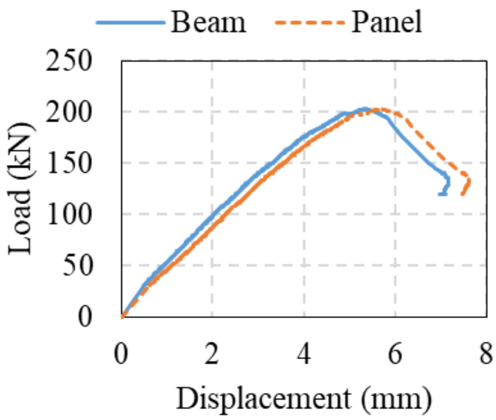
Figure 9 Shear enhancement of beams with various connection details



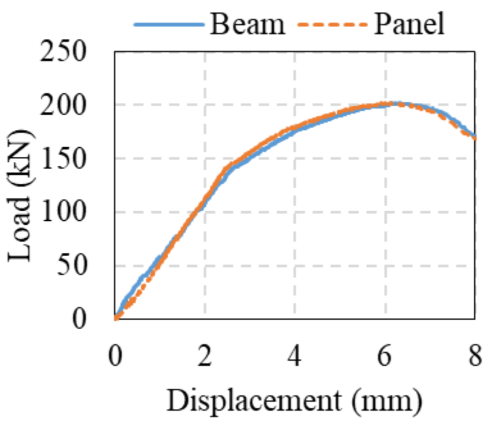
(a) 1.5F-Epoxy



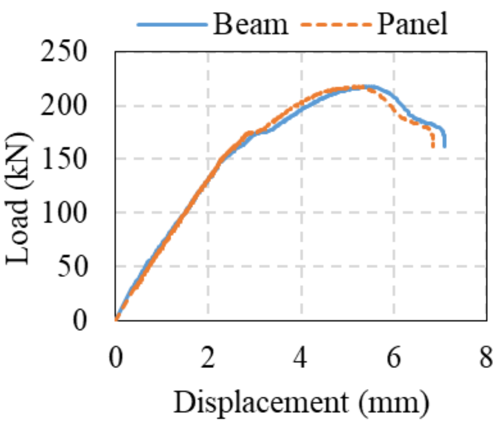
(b) 1.5F-4D12



(c) 1.5F-6D12



(d) 1.5F-6D10



(e) 1.5F-8D10

Figure 10 Load versus vertical displacement of RC beam and SFRC panel with various connection detail

4. Analysis Using Finite Element Method (FEM)

4.1 Analytical cases

Finite-element (FE) modeling of strengthened RC beams was carried out using FE software package ABAQUS. Control beam without SFRC panels was modeled first and validated with the experimental results in order to ensure capacity of program and characteristic of concrete and steel properties. Then, finite-element analysis was performed for all the specimens in experimental part and six other cases were also analyzed as parametric study. Table 6 lists the details of the beams for parametric study. Effects of panel thickness (Series I), compressive strength of SFRC (Series II), number of bolts and bolt pattern (Series III) were considered in numerical study. Geometry and bolt pattern of specimens in series I and II are same as those of 1.5F-8D12. Bolt patterns of specimens in series III are illustrated in Fig. 11.

Table 6 Details of analytical beams and results

Series	Name	SFRC panels Thickness (mm)	f_c' (MPa)	f_t (MPa)	No. of bolts	P_{FEM} (kN)	V_{FEM} (kN)	Shear enhancement ratio
I	B1	15	70	5.24	8	222.8	111.4	2.06
	B2	20	70	5.24	8	227.3	113.6	2.10
II	B3	10	50	4.95	8	202.8	101.4	1.87
	B4	10	90	6.64	8	221.4	110.7	2.04
III	B5	10	70	5.24	4	186.4	93.2	1.72
	B6	10	70	5.24	10	208.8	104.4	1.93

(a) B5 (b) B6

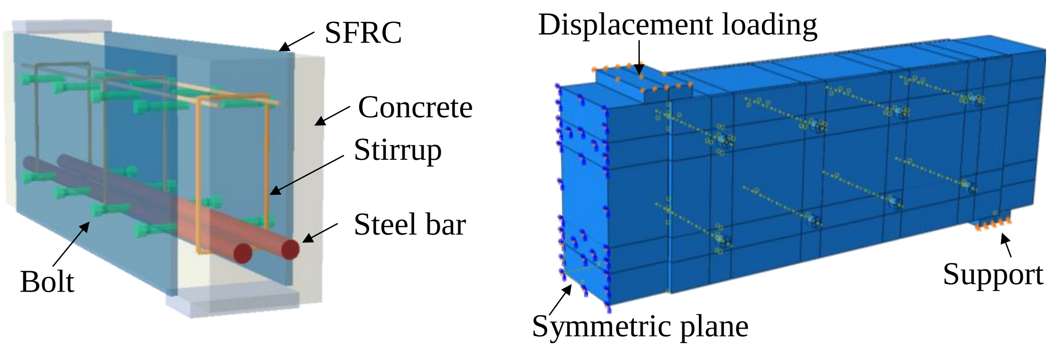
Figure 11 Bolt pattern of specimens in series III (unit: mm)

4.2 Analytical model

The three-dimensional (3D) FE model was developed. Due to symmetry of the beams, a half of the specimen was modeled as shown in Fig. 12(a). Concrete and SFRC elements were modeled using 8-node brick element with reduced integration (C3D8R) and 2-node truss element (T3D2) was used for steel reinforcement and stirrups. Longitudinal steel bars were embedded in concrete element at the specified location without considering the bond slip between two elements. Geometric tolerance was set to be 0.07. Bolts were modeled using 8-node brick element with reduced integration (C3D8R). Cohesive surfaces defined through the contact area were used to model the concrete-SFRC and concrete-bolt interfaces.

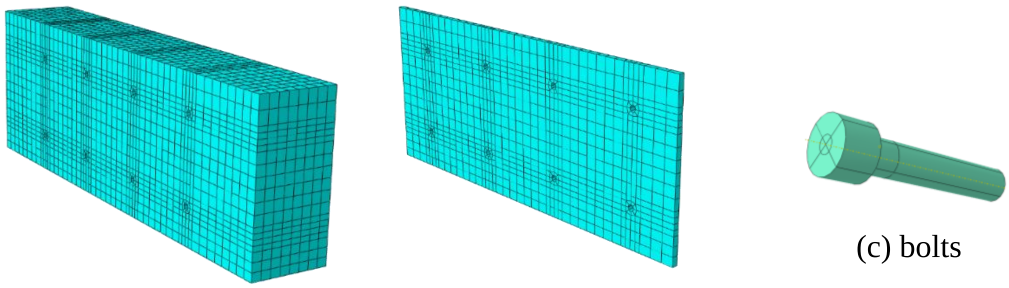
Mesh convergence study was carried out to examine the optimal mesh size. The results show that further decrease in the mesh size has little effect on the numerical results. Consequently, mesh size of concrete and panels was 20 mm in general and 5 mm for region near bolts as presented in Fig. 13.

Figure 12(b) shows loading and boundary condition of the model. Symmetric boundary condition was applied at the plane representing the continuous of beam. This includes the restrictions of translation along x-axis and rotation about z-axis. Roller support and loading plates were also modelled. The FE analysis was carried out with displacement control method.



(a) FE model for 1.5F-8D12 (b) Loading and boundary condition

Figure 12 FE model



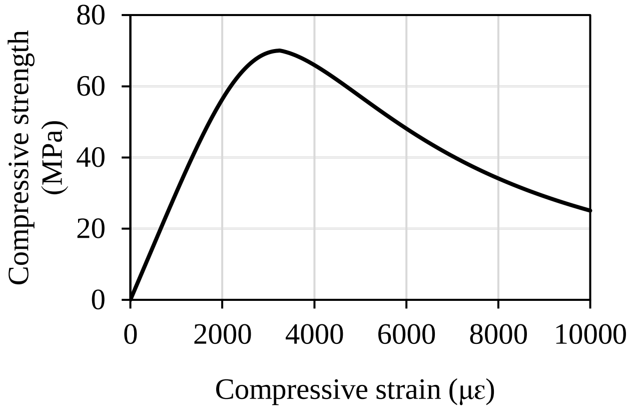
(a) Concrete (b) SFRC (c) bolts

Figure 13 FE mesh

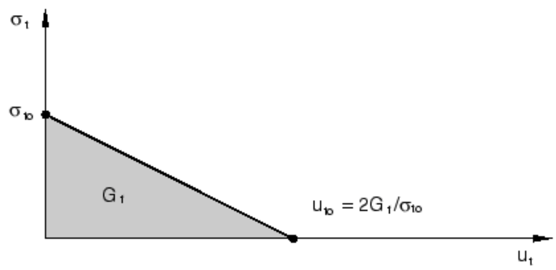
4.3 Material properties

In order to model the behavior of concrete, the concrete damage plasticity (CDP) was used. It is based on two main failure mechanisms which are tensile cracking and compressive crushing of concrete. The CDP parameters were: Poisson's ratio (0.2), the dilation angle (36°), the flow potential eccentricity (0.1), the ratio of initial equibiaxial compressive yield stress to initial uniaxial compressive yield stress (1.16), the ratio of the second stress invariant on the tensile meridian to that on the compressive meridian (0.667), and viscosity parameter (0.001). The stress-strain curve of concrete in compression was simulated by the model proposed by Hognestad [21] with a maximum stress equal to 32 MPa, ultimate compressive strain equal to 0.0035 and a young modulus of 27 GPa. The tensile behavior was modeled using a linear elastic branch until the tensile strength. After crack initiation, the fracture energy cracking model was adopted. The fracture energy was calculated from the equation proposed by Bazant and Becq-Giraudon [22]. The tensile strength of concrete was 3.26 MPa and the fracture energy was 1.79 N/mm.

Concrete damage plasticity was also used to simulate the behavior of steel fiber reinforced concrete. The behavior of SFRC in compression was expressed by the model proposed by Lee et al. [23] as presented in Fig. 14(a). The tensile properties of SFRC consisted of a linear elastic behavior until tensile strength and linear softening behavior after crack initiation (Fig. 14(b)). The post-failure behavior for direct straining across cracks was specified by applying a fracture energy cracking criterion, which was calculated from the equations proposed by Kovar and Foglar [24]. Compressive and tensile strengths of SFRC are listed in Table 6. Other material properties of SFRC for numerical model are: Poisson's ratio = 0.31 [25], young's modulus = 31 GPa [23], fracture energy = 4.05 N/mm, 7.30 N/mm and 8.82 N/mm for steel fiber volume fraction = 0%, 1.0% and 1.5%, respectively.



(a) Compression



(b) Post-failure stress-fracture energy curve [26]

Figure 14 Material model of SFRC

The longitudinal and shear reinforcements were modeled by a bilinear elastic-perfectly plastic model. Yield strength and young modulus were described in section 2.3. The stress–strain behavior of bolts is linear elastic material until yielding, followed by plastic behavior. The modulus of elasticity and yield stress for bolts were taken as 200 GPa and 520 MPa, respectively.

Cohesive surface was used to define the surface to surface contact between concrete-SFRC and concrete/SFRC-bolts. This model determined the potential surfaces of separation by traction-separation constitutive model as presented in Fig. 15. For the contact between concrete and SFRC, stiffness coefficient was 4600 N/mm^3 and separation at failure was 0.4 mm. Stiffness coefficient of interface between bolts and concrete/SFRC was 4000 N/mm^3 and separation at failure was 0.06 mm.

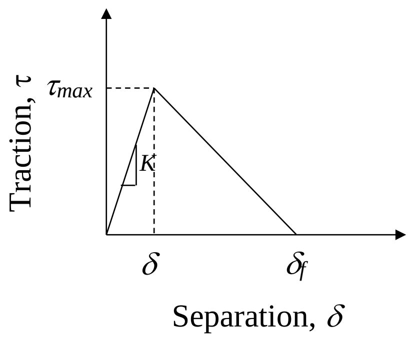
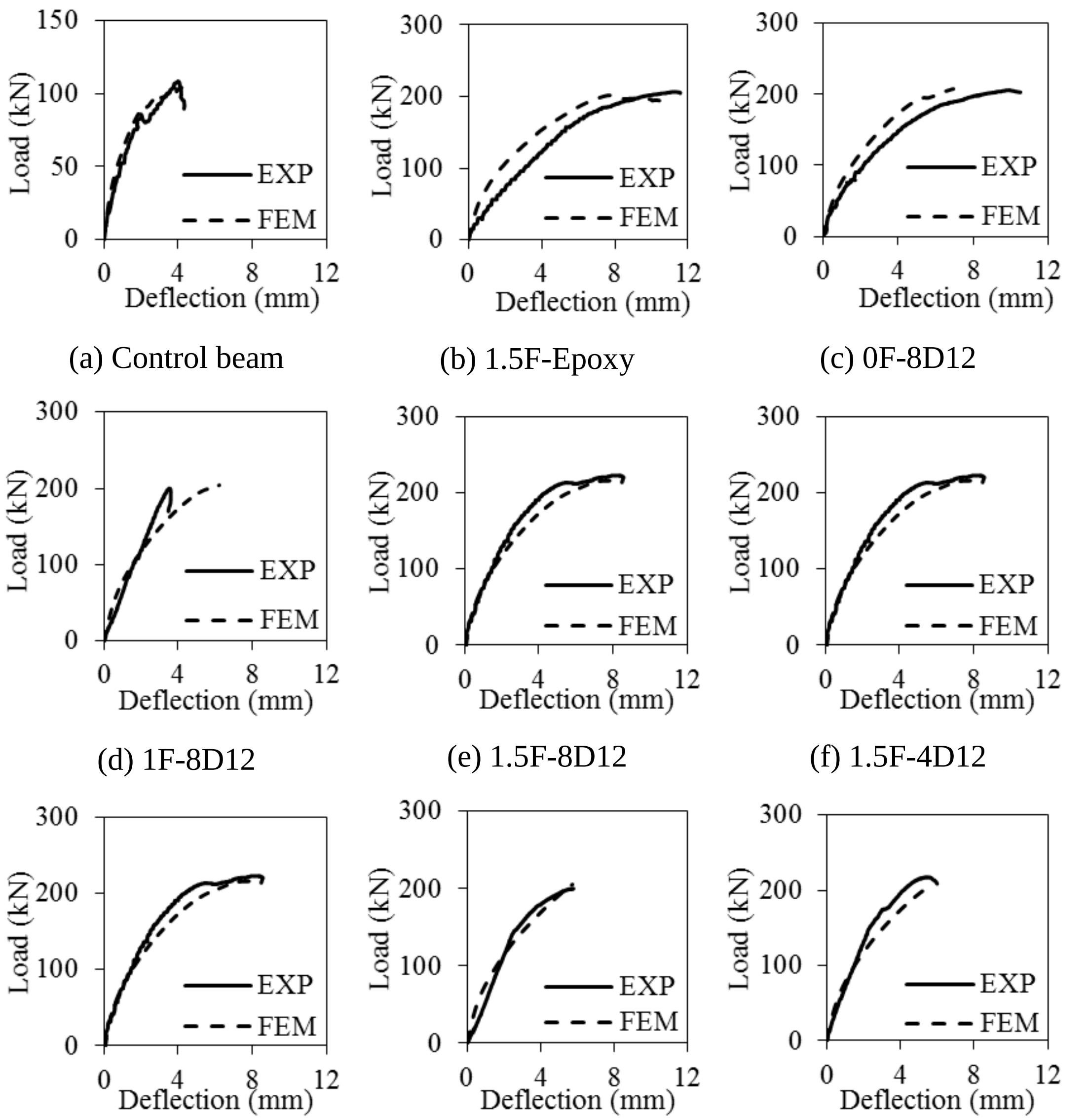


Figure 15 Traction-separation cohesive material law

4.4 Analytical results and discussions

4.4.1 Verification of the FE model

Figure 16 presents experimental and numerical comparison of the load versus mid-span deflection curves of all specimens. As seen from the figures, the experimental load-deflection curves showed good agreement especially for ultimate load capacity compared with the FE analysis of control beam and SFRC strengthening beams. Values of analytical shear capacity (V_{FEM}) are summarized in Table 5. As seen in Table 5, a maximum deviation of analytical shear capacity compared with experimental shear capacity was 6%. Crack pattern of specimens observed from experiment and FE analysis is presented in Table 4. Numerical crack pattern of control beam reveals a shear crack in shear span. For the strengthened specimens, crack patterns on SFRC panels were presented. Stress contour of 1.5F-Epoxy was different compared with results of other specimens due to debonding of SFRC panels. In other strengthened specimens, it is observed that diagonal cracks normally passed through the bolts. This behavior is also observed in the experiment. Therefore, crack patterns are reasonably captured from FE analysis. From this verification, it is proved that the FE model is appropriate to describe the shear behavior of RC beams strengthened by SFRC panels.



(a) Control beam (b) 1.5F-Epoxy (c) 0F-8D12

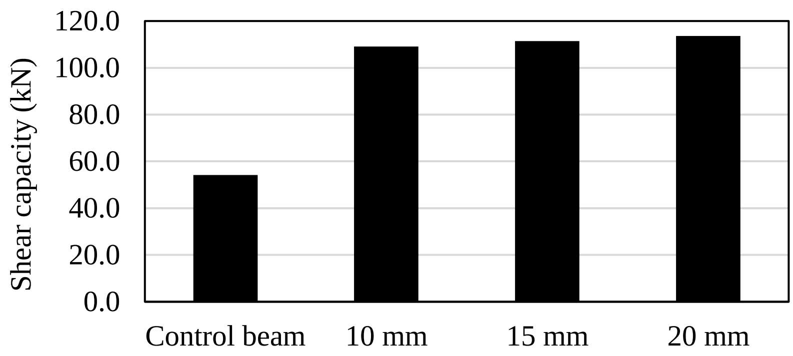
(d) 1F-8D12 (e) 1.5F-8D12 (f) 1.5F-4D12

(g) 1.5F-6D12 (h) 1.5F-6D10 (i) 1.5F-8D10

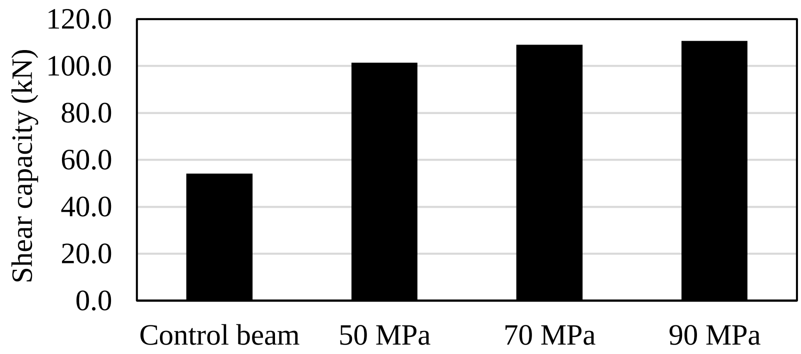
Figure 16 Load-midspan deflection comparison for tested beams

4.4.2 Parametric study

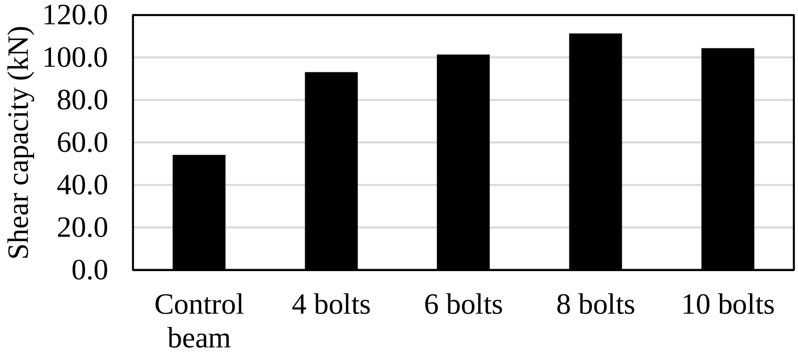
The numerical analysis was extended to determine the effects of panel thickness, compressive strength of SFRC, number of bolts and bolt pattern. Shear capacity of all analytical beams is listed in Table 5 and effects of the parameters are presented in Fig. 17. The results shows that there was an insignificant improvement of shear capacity when the thickness of panels increased from 10 mm to 15 mm and 20 mm (see Fig. 17(a)). It is because the shear contribution due to steel fibers depended on diagonal crack shape which is mainly governed by the bolt pattern. Therefore, the increase in panel thickness give relatively small contribution compared with the total shear capacity of the beams. The shear enhancement ratios of specimens with f'_{c_SFRC} = 50, 70 and 90 MPa were 1.87, 2.01, and 2.04, respectively. The shear capacity was almost the same when the compressive strength of SFRC panels exceeded 70 MPa as shown in Fig. 17(b). Figure 17(c) plots the shear capacity of beams with different number of bolt per panel. Noted that only the specimens with symmetrical bolts pattern (i.e., B5, 1.5F-6D12, 1.5F-8D12, and B6) are compared in this figure. The results show that in case of symmetrical bolts pattern the shear capacity increased when the number of bolts increased from 4 to 8 bolts. However, the shear capacity decreased when the number of bolts became 10 bolts per panel because providing many bolts per panel reduced area of SFRC panels and bolt spacing. Crack can easily connect between bolts when bolt spacing decreased as observed from crack pattern of B6 in Fig. 18(d). In the case of the smaller number of bolts, diagonal bolt pattern (1.5-4D12) gave considerably higher shear capacity than symmetrical pattern (B5) as illustrated in Fig. 17(d).



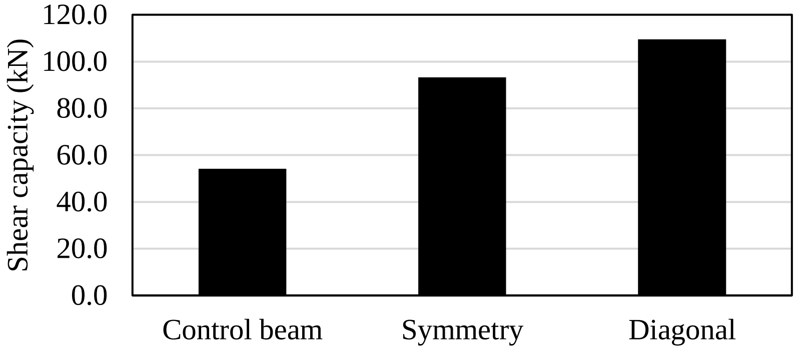
(a) Effect of panel thickness



(b) Effect of compressive strength of SFRC

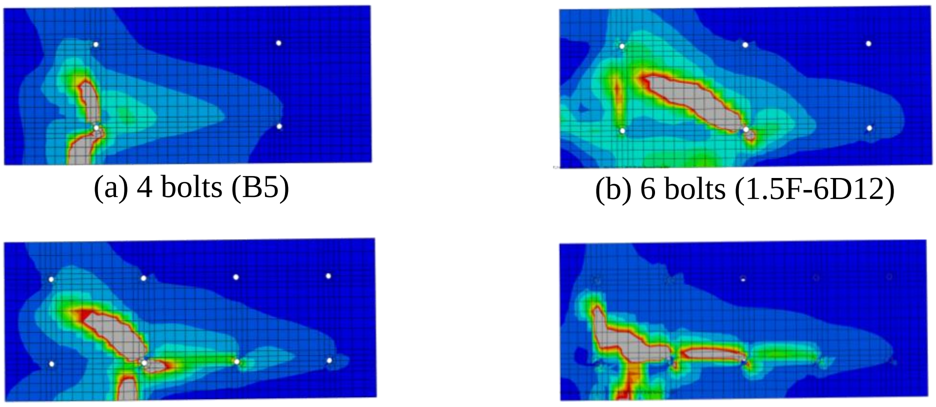


(c) Effect of number of bolts (symmetry bolt pattern case)



(d) Effect of bolt pattern

Figure 17 Results of parametric study



(a) 4 bolts (B5)   (b) 6 bolts (1.5F-6D12)

(c) 8 bolts (1.5F-8D12)   (d) 10 bolts (B6)

Figure 18 Crack pattern of the panels with different number of bolts

5. Conclusions

1. Shear capacity and beam stiffness under service load of RC beams remarkably increased when RC beams were strengthened using steel fiber reinforced concrete panels. This technique is effective to enhance the shear performance of RC beams.

2. Effect of steel fibers pronounced when the volume fraction of fiber was 1.5%. The resistance to crack of panels increased due to addition of steel fibers.
3. Shear capacity of specimens with epoxy combined with bolts connection was comparable with those of specimen with epoxy connection. However, the failure mode of the specimens was completely changed. Specimen with epoxy connection exhibited debonding failure of SFRC panel at the ultimate load and thus using only epoxy for connection is not recommended. Using epoxy combined with bolts connection can prevent debonding failure and also improve beam stiffness under service load.
4. The load-displacement relationships obtained from finite element analysis were in close agreement with the experimental results. This indicates that the presented numerical modelling procedure can be used for predicting the shear behavior of RC beams strengthened using SFRC panels up to ultimate stage.
5. The experimental and analytical results show that the shear capacity increased with the increase in number of bolts up to 8 bolts per panel and compressive strength of SFRC up to 70 MPa. The further increase beyond these values shows another tendency. Bolts patterns strongly affected the shear behavior of the beams. Diameter of bolts and panel thickness insignificantly effected the shear capacity of strengthened beams.

Acknowledgement

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References

[1] Pham, H., Al-Mahaidi, R., Experimental investigation into flexural retrofitting of reinforced concrete bridge beams using FRP composites, *Composite Structures*, Vol. 66, No. 1–4, 2004, pp. 617-625, https://doi.org/10.1016/j.compstruct.2004.05.010.

[2] Al-Saidy, A.H., Al-Harthy, A.S., Al-Jabri, K.S., Abdul-Halim, M., Al-Shidi, N.M., Structural performance of corroded RC beams repaired with CFRP sheets,

Composite Structures, Vol. 92, No. 8, 2010, pp. 1931-1938, https://doi.org/10.1016/j.compstruct.2010.01.001.

[3] Chen, J.F., Teng, J.G., Shear capacity of FRP-strengthened RC beams: FRP debonding, *Construction and Building Materials*, Vol. 17, No., 2003, pp. 27-41, https://doi.org/10.1016/S0950-0618(02)00091-0.

[4] Balaguru, P., Narahari, R., Patel, M., Flexural toughness of steel fiber reinforced concrete, *ACI Material Journal*, Vol. 89, No. 6, 1992, pp. 541-546.

[5] Li, V.C., Ward, R., Hamaza, A.M., Steel and synthetic fibers as shear reinforcement, *ACI Materials Journal*, Vol. 89, No. 5, 1992, pp. 499-508.

[6] Wafa, F.F., Ashour, S.A., Mechanical properties of high-strength fiber reinforced concrete, *ACI Material Journal*, Vol. 89, No. 5, 1992, pp. 449-455.

[7] Bischoff, P.H., Tension stiffening and cracking of steel fiber-reinforced concrete, *Journal of Materials in Civil Engineering*, Vol. 15, No. 2, 2003, pp. 174-182.

[8] Thomas, J., Ramaswamy, A., Mechanical properties of steel fiber-reinforced concrete, *Journal of Materials in Civil Engineering*, Vol. 19, No. 5, 2007, pp. 285-392, https://doi.org/10.1061/(ASCE)0899-1561(2007)19:5(385).

[9] Meda, A., Mostosi, S., Riva, P., Shear strengthening of reinforced concrete beam with high-performance fiber-reinforced cementitious composite jacketing. *ACI Structural Journal*, Vol. 111, No. 5, 2014, pp. 1059–1067.

[10] Meda, A., Mostosi, S., Rinaldi, Z., Riva, P., Corroded RC columns repair and strengthening with high performance fiber reinforced concrete jacket. *Materials and Structures*, Vol. 49, No. 5, 2016, pp. 1967–1978, https://doi.org/10.1617/s11527-015-0627-1.

[11] Martinola, G., Meda, A., Plizzari, G.A., Rinaldi, Z., Strengthening and repair of RC beams with fiber reinforced concrete, *Cement and Concrete Composites*, Vol. 32, No. 9, 2010, pp. 731–739, https://doi.org/10.1016/j.cemconcomp.2010.07.001.

[12] Kobayashi, K., Rokugo, K., Mechanical performance of corroded RC member repaired by HPFRCC patching, *Construction and Building Materials*, Vol. 39, 2013, pp. 139-147, https://doi.org/10.1016/j.conbuildmat.2012.05.013.

[13] Hussein, M., Kunieda, M., Nakamura H., Strength and ductility of RC beams strengthened with steel-reinforced strain hardening cementitious composites, *Cement and Concrete Composites*, Vol. 34, 2012, pp. 1061-1066, https://doi.org/10.1016/j.cemconcomp.2012.06.004.

[14] Ferrari, V.J., Hanai, J.B., Souza, R.A., Flexural strengthening of reinforcement concrete beams using high performance fiber reinforcement cement-based composite (HPFRCC) and carbon fiber reinforced polymers (CFRP), *Construction and Building Materials*, Vol. 48, 2013, pp. 485-498, https://doi.org/10.1016/j.conbuildmat.2013.07.026.

[15] Wirojjanapirom, P., Matsumoto, K., Kono, K., Niwa, J., Experimental study on shear behavior of RC beams using U-shape UFC permanent formwork with shear keys and bolts. *Journal of Japan Society of Civil Engineers, Ser. E2 (Materials and Concrete Structures)*, Vol. 69, No. 1, 2013, pp. 67-81, https://doi.org/10.2208/jscejmcs.69.67.

[16] Ruano, G., Isla, F., Pedraza, R. I., Domingo, S., Luccioni, B., Shear retrofitting of reinforced concrete beams with steel fiber reinforced concrete, *Construction and Building Materials*, Vol. 54, 2014, pp. 646-658, https://doi.org/10.1016/j.conbuildmat.2013.12.092.

[17] Al-Salloum, Y.A., Elsanadedy, H.M., Alsayed, S.H., Iqbal, R.A., Experimental and numerical study for the shear strengthening of RC beams using textile reinforced mortar, *Journal of Composites for Construction*, Vol. 16, No.1, 2012, pp. 74-90, https://doi.org/10.1061/(ASCE)CC.1943-5614.0000239.

[18] Escrig, C., Gil, L., Bernat-Maso, E., Puigvert, F., Experimental and analytical study of reinforced concrete beams shear strengthened with different types of textile-reinforced mortar, *Construction and Building Materials*, Vol. 83, 2015, pp. 248-260, https://doi.org/10.1016/j.conbuildmat.2015.03.013.

[19] Ombres, L., Structural performances of reinforced concrete beams strengthened in shear with a cement based fiber composite material, *Composite Structures*, Vol. 122, 2015, pp. 316-329, https://doi.org/10.1016/j.compstruct.2014.11.059.

[20] Chalioris, C.E., Thermou, G.E., Pantazopoulou, S.J., Behaviour of rehabilitated RC beams with self-compacting concrete jacketing – Analytical model and test results, *Construction and Building Materials*, Vol. 55, 2014, pp. 257-273, https://doi.org/10.1016/j.conbuildmat.2014.01.031.

[21] Hognestad, E., Study of combined bending and axial load in reinforced concrete members, University of Illinois at Urbana Champaign, College of Engineering. Engineering Experiment Station, 1951.

[22] Bažant, Z.P., Becq-Giraudon, E., Statistical prediction of fracture parameters of concrete and implications for choice of testing standard. *Cement and Concrete*

Research, Vol. 32, No. 4, 2002, pp. 529-55, https://doi.org/10.1016/S0008-8846(01)00723-2

[23] Lee, S.C., Oh, J.H., Cho, J.Y., Compressive behavior of fiber-reinforced concrete with end-hooked steel fibers. *Materials*, Vol. 8, No. 4, 2015, pp. 1442-1458, https://doi.org/10.3390/ma8041442

[24] Kovar, M., Foglar, M., An analytical description of the force–deflection diagram of FRC. *Composites Part B: Engineering*, Vol. 69, 2015, pp. 550-561, https://doi.org/10.1016/j.compositesb.2014.10.021

[25] Padmarajaiah, S. K., Influence of fibers on the behavior of high strength concrete in fully/partially prestressed beams: an experimental and analytical study. Ph.D. thesis, Indian Institute of Science, Bangalore, India, 1999.

[26] ABAQUS documentation, ABAQUS 2016, USA: Hibbitt, Karlsson and Sorensen; 2015.

COMPARISONS OF CONNECTION TYPES ON SHEAR CAPACITY OF RC BEAMS STRENGTHENED BY STEEL FIBER REINFORCED CONCRETE PANELS

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ABSTRACT

Shear behavior of reinforced concrete (RC) beams strengthened by precast steel fiber reinforced concrete (SFRC) panelsis studied. The objective of this paper is to investigate effects of connection types and strengthening material on shear behavior of the beams. One reference beam and three RC beams strengthened by panels were subjected to four-point bending test. The panels were prepared in advance and attached to both side of the beams. Mortar and SFRC were chosen asthe strengthening materials. For SFRC, two types of connections, which are epoxy and epoxy combined with bolts, were tested in this study. The experimental results show that shear capacity approximately increasedby twice after strengthening for all connection types. With using steel fiber reinforced concrete panels, it could effectively enhance the shear capacity of RC beam. In particular, the bolt connection revealedthe highest shear capacity and offered least deboning.

Keywords: Fiber reinforced concrete, strengthening, RC beams, precast panel, shear capacity.

1. INTRODUCTION

The rehabilitation of reinforced concrete (RC) structures is needed more often over the last decadebecauseof deteriorationof concrete, changing in use of structures or development of design requirements. The selection of strengthening materials and retrofitting method is an important issue that affects the achievement of strengthening. Fiber reinforced concrete (FRC) is one of the outstanding composite materials in concrete structures since short fibers can enhance tensile strength, energy absorption and improve cracking control of concrete (Thomas and Ramaswamy 2007). Recently, fiber reinforced concrete and fiber reinforced cementitious composite have been used for strengthening and repairing of RC structures as published by many researchers (Ferrari et al. 2013, Hussein et al. 2012 and Martinola et al. 2010). According to the literature, the flexural performance was significant improved after retrofitting. These researches; however, focused on the flexural behavior of the beams.

Shear failure of RC structures is well-known for itsbrittle failure mode and should be avoided since it induces quick load-decrement after the initiation of diagonal crack.

Wirojjanapirom et al. (2013) proposed to use ultra-high strength fiber reinforced concrete permanent formwork to enhance the shear capacity for the construction. While the shear strengthening by steel fiber reinforced concrete (SFRC) jacketinghas been presented by Ruano et al. (2014). In this literature, the SFRC jacketing was cast-in-place. At the present, due to the high labor cost, the strengthening method using precast technique become more interesting. By combining the precast technique with the excellent mechanical properties of FRC, the structural performance can be improved and construction time and cost can be reduced. However, the strengthening method using precast SFRC panels has not been clearly investigated.

The objective of this study is therefore to explore the strengthening effect of SFRC panels attached on RC beams. The influence of connection types and strengthening material on shear behavior of the strengthened beamsare investigated. Static loading tests of RC beams strengthened by precast panels were carried out. Shear capacity and failure mechanism arediscussed based on the experimental results.

2. EXPERIMENTAL PROCEDURE

2.1. Test specimens

The experimental program consisted of four reinforced concrete rectangular beams. All beams were designed to fail in shear. Figure 1 shows the dimension and reinforcing bar arrangement of a RC beam. Each specimen was 1,800 mm long with a 150 × 300 mm cross section. The shear span (*a*) was 700 mm and the effective depth (*d*) was 250 mm. All specimens were controlled such that they would fail in the left shear span by providing fewer stirrups in the left shear span as shown in Figure 1. The stirrup ratio in the test span was 0.12% in all specimens.

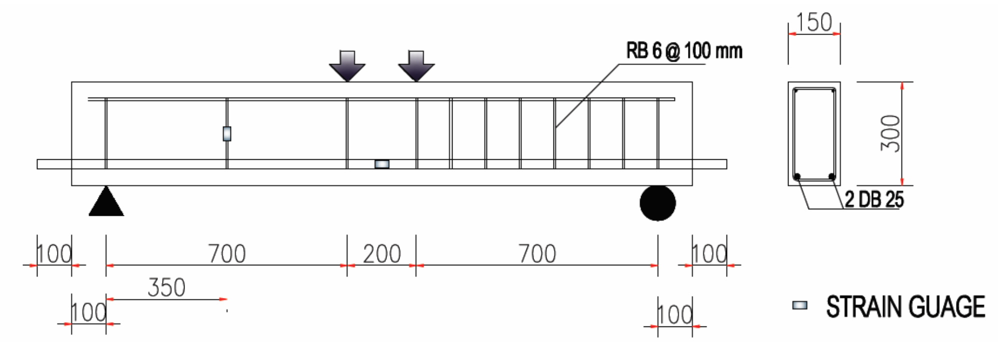


Figure 1: *Detailed diagram of a RC beam (Unit: mm)*

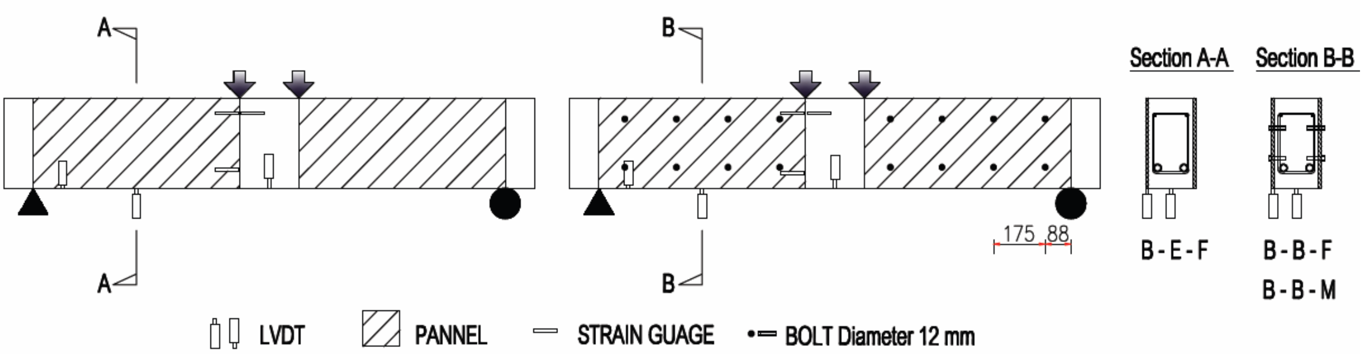


Figure 2: *Detail of strengthened specimens (Unit: mm)*

Experimental cases are listed in Table 1. One of the specimen was used as the reference beam (BC) while the 10 mm thick panels were attached on both sides of other beams (i.e., B-E-F, B-B-F and B-B-M). The location of panel is illustrated in Figure 2. Two types of connection between RC beams and panel, which are epoxy and bolts with epoxy, were considered. SFRC were used in B-E-F and B-B-F, while mortar was used in B-B-M. The precast panels were prepared in advance. Surface treatment has been done before installation of the panels.

Table 1: Experimental cases and properties of beams

Specimen	Parameters		Properties of concrete		Properties of panels			
	Connection	Material	f'_c (MPa)	f_t (MPa)	Thickness (mm)	Fiber content (%)	f'_c (MPa)	f_t (MPa)
BC	-	-	32.4	3.26	-	-	-	-
B-E-F	Epoxy	FRC	32.4	3.26	10	1.5	61.8	6.28
B-B-F	Epoxy +Bolt	FRC	32.4	3.26	10	1.5	60.8	5.24
B-B-M	Epoxy +Bolt	Mortar	32.4	3.26	10	-	56.8	4.33

Meaning of the specimen's name: (**B**eam)-(**E**poxy/**B**olt with epoxy)-(**F**RC/**M**ortar)

2.2. Material

The 28-day compressive strength of the concrete used in RC beams was 32.4 MPa. The longitudinal reinforcing bars were made of deformed steel having 25.4-mm nominal diameter and 502-N/mm^2 yield strength. Stirrups and compression bars made of round steel that was 6mm in nominal diameter were arranged as the shear reinforcement. Their yield strength exceeded 235 N/mm^2.

Mortar used in panel were high strength mortar. The 35-mm steel fibers are used in this study. The properties of steel fibers are summarize in Table 2. The volume fraction of fibers was equal to 1.5% of the full volume of the concrete in all specimens. Epoxy was high-modulus, high-strength and structural epoxy paste adhesive. In addition, the chemical bolts of 12-mm diameter were used.

Table 2: Properties of steel fibers

Type	Length (mm)	Diameter (mm)	Aspect ratio	Tensile strength (MPa)	E (GPa)	Shape of the end
Steel	35	0.55	65	1050	210	Hooked

Experimental setup and instrumentation

Specimens were subjected to a four-point bending with a simply-supported condition. Figure 2 shows the detailed loading arrangement along with the locations of loading points and strain gauges. The measuring parameters were applied load, displacements of mid-span and supporting points using the transducers and strain of the longitudinal steel bars and stirrups. The strain of the longitudinal steel bars was measured at mid-span using strain gauges, whereas the strains of stirrups were measured at the middle height of stirrups as presented in Figure 1. Moreover, the surface strain and the displacement of panels and RC beams were recorded as illustrated in Figure 2.

3. RESULTS AND DISCUSSION

3.1. Load-deflection relationships

Relationship between applied load and mid-span deflection is presented in Figure 3. Mid-span deflection was calculated by subtracting displacements at supporting point from mid-span displacement. Load-deflection response was linear prior to cracking. After the initiation of the first flexural cracking, the load-deflection response became nonlinear. In BC, there was a slight drop of the load when diagonal crack initiated. After that, the load increased until peak and sudden shear failure occurred. On the other hand, the beams strengthened by panels provided longer nonlinear load-displacement curve as shown in Figure 3. Inpre-peak region, the inclination of the load-deflection curve decreased. Then, shear failure was observed in all specimen.

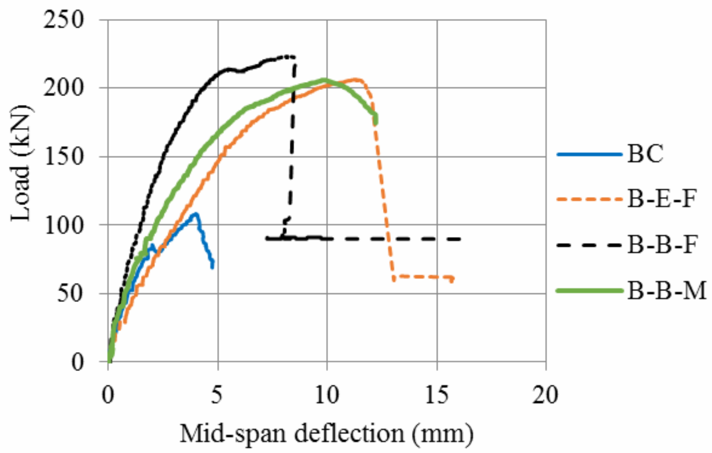


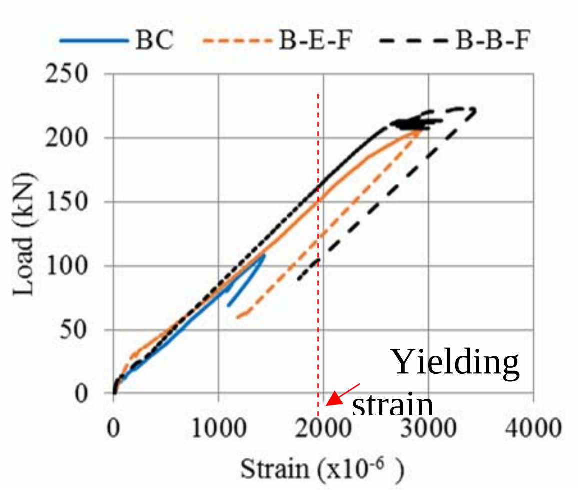
Figure 3: *Load-deflection curves*

It was found that the longitudinal bars have not yielded in BC but they yielded in B-E-F and B-B-F at 90% of peak load as illustrated in Figure 4. The stirrup strain is plotted in Figure 5. Stirrups in all specimens yielded just before peak load. The yielding loads of stirrups are summarized in Table 3. The yielding of stirrups can be delayed when the RC beams are strengthened by the panels. It is because panels help resist shear force.

Table 3: Experimental results

Specimen	Yielding load		Maximum load, P_{max}	V_{exp}	V_c+V_s	V_{panel}	V_{exp}/V_{BC}
	Longitudinal bars (kN)	Stirrups (kN)	(kN)	(kN)	(kN)	(kN)	
BC	Not yield	87.0	108.4	54.19	54.19	0	1.00
B-E-F	189.0	198.7	206.6	103.29	54.19	49.10	1.91
B-B-F	203.1	220.5	222.7	111.38	54.19	57.19	2.05
B-B-M	-*	201.5	206.0	103.00	54.19	48.81	1.90

* Strain gauge was broken.



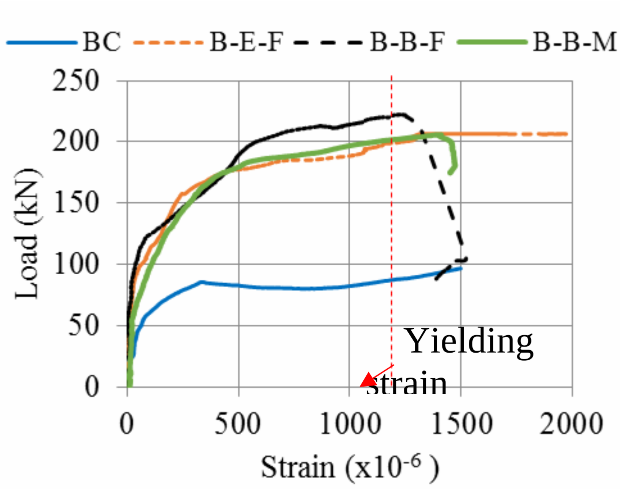


***Figure 4:** Strain of longitudinal reinforcement*

***Figure 5:** Stirrup strain*

Furthermore, downward displacements of RC beams and panels was measured using transducers as mentioned in section 2.3. Figure 6 presents displacements of RC beams and panels. For the epoxy connection (B-E-F), panel's displacement was slightly greater than that of the RC beam until 80% of maximum load ($0.8P_{max}$). After that, displacement of RC beam became greater than panel. It can be implied that, beyond this point, RC beam and panel did not show composite behavior. On the other hand, when using bolts to connect SFRC panels with the beams (B-B-F), the downward displacement of beam and panel became identical until nearly the peak load as seen in Figure 6(b). However, when mortar panels were used, the displacements of beam and panel were different.

3.2. Cracking behavior

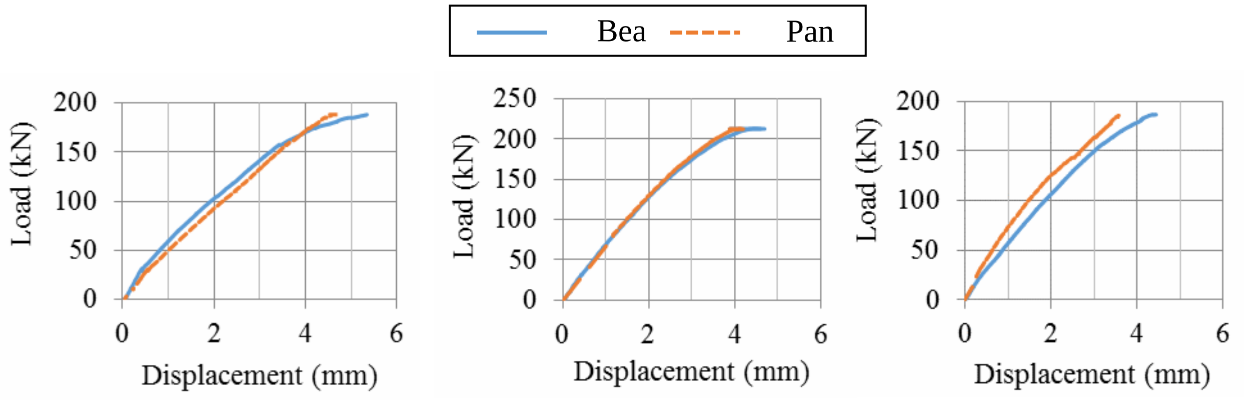
Cracking behavior and crack pattern of each specimen are different because of the effect of connection types and materials used in panels. The failure behavior is explained in this section.

In BC which is a conventional RC beam with stirrups, the flexural crack was observed around tension fiber at mid-span. Load still increased until the initiation of the diagonal crack. Diagonal crack propagated from the support to the loading point as shown in Figure 7(a). Diagonal tension failure occurred when the load was 108.4kN.

In B-E-F, flexural cracks were observed in the panel. The deflection increased with the increased in applied load. At the peak load, one panel fell off as shown in Figure 7(b) and there was the critical diagonal crack in the RC beams.

In B-B-F (Figure 7(c)), from the beginning, specimen behaved in elastic manner until the first flexural crack that occurred around mid-span. With increase in load, moreflexural cracks were observedin the panels near the location of bolts. When load reached to the peak, main inclined crack penetrated from tension fiber and passed the bolt to loading point. The concrete in compression zoned was crush.

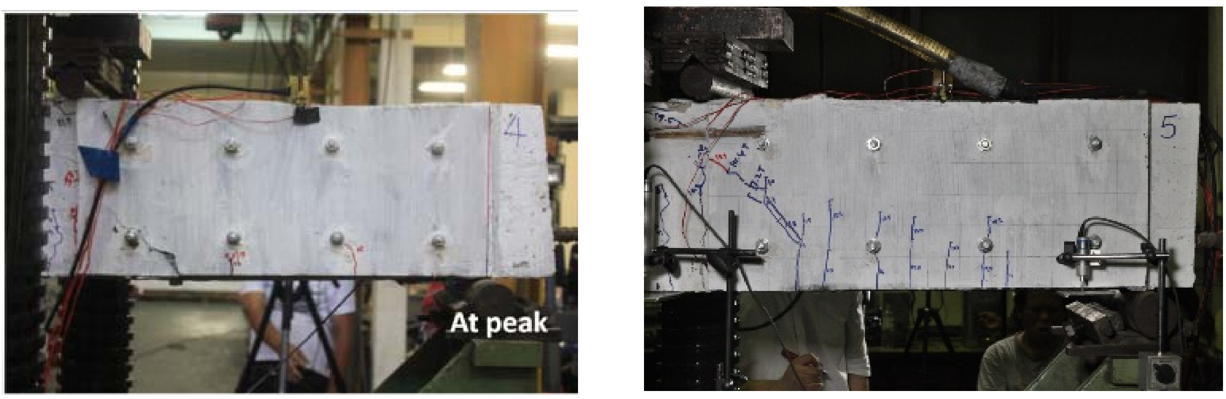
Before the initiation of flexural cracks, B-B-M shows same behavior with B-E-F and B-B-F. Unlike the specimens strengthened by SFRC, a number of cracks were observed in the mortar panels. The cracks initiated from tension fiber and penetrated vertically to compression zone. The diagonal crack was observed in the panel and compression zone was crush nearly the peak load.



(a) B-E-F (b) B-B-F (c) B-B-M

Figure 6: *Comparison of displacement of RC beams and panels*

(a) BC (b) B-E-F



(c) B-B-F (d) B-B-M

Figure 7: *Picture of specimens at peak load*

3.3. Shear capacity

Modifying from shear model of the conventional RC beams, it is assumed that shear capacity of RC beams strengthened by SFRC panels (V) can be calculated from Equation (1). Applied shear force is resisted by three components which are shear capacity of beams without stirrups (V_c), shear carried by stirrups (V_s) and shear carried by panels (V_{panel}).

$$V = V_c + V_s + V_{panel} \tag{1}$$

Table 3 presents the results of loading tests. Since BC consists of only concrete and stirrups, shear capacity of BC is equal to V_c+V_s. The shear capacity of BC is used as reference value for V_c+V_s. The shear capacity resisted by panels (V_{panel}), thus, can be calculate from Equation (2).

$$V_{panel} = V_{exp} - V_c - V_s \tag{2}$$

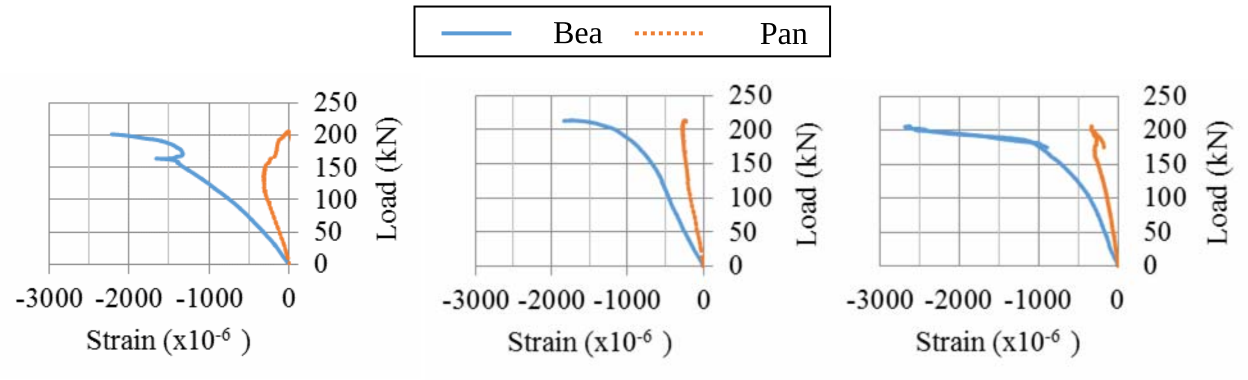
Where, V_{exp} is shear capacity from the experiment.

The shear capacity of strengthened beams dramatically increased comparing with reference beam (V_{BC}). This strengthening method can enhance shear capacity 1.9-2.0 times. Shear capacityof the beam strengthened by SFRC panelswith epoxy combined with boltswas the largest among all specimens.

3.4. Effect of connection types and materials

Influence of connection types can be discussed from B-E-F (epoxy) and B-B-F (epoxy combined with bolts). By using bolt connection between RC and panels, stiffness and shear capacity of the beam can be improved as shown in Figure 3. It is because bolts help transfer shear force to panel. Unlike B-E-F, there was no debondingfailure at the peak load between panel and beams in B-B-F. Debonding failure in B-E-F are dangerous and unsafe. Thus, it is not recommended toprovide only epoxy in the connection.

Moreover, surfacestrains of concrete and panel below loading point were measured at the location shown in Figure 2. Based on the experimental results, it was found that the concrete strain of RC beams was much larger than the strain at the boundary of panels in all cases as presented in Figure 8. is concluded that the panelsdid not fully work especially at the boundary of panels. The efficiency of the strengthening can be improved if all part of panels resists the load.



(a) B-E-F (b) B-B-F (c) B-B-M

Figure 8: *Strain on concrete and panel surface*

It Effect of fibers in panels can be discussed by comparing B-B-F and B-B-M. Shear capacity of beams strengthened by SFRC panels was 1.16 times higher than that of beam strengthening by mortar panels. A number of cracks were observed when using mortar panels because there were no fibers to resist the propagation of cracks.

4. CONCLUSIONS

1) The shear capacity of RC beams strengthened by SFRC panels increased drastically. Itis because panelscan help carrying shear force and resisting the opening of the diagonal crack in RC part.

2) The specimen with epoxy combined with boltsrevealed the highest shear capacity. Using both epoxy and bolts is recommended because the panels are still compatible with the RC beam untilthe ultimate state.

3) Efficiency of steel fiber reinforced concrete (SFRC) panels is better than mortar panels since steel fibers can enhance tensile strength and increase resistanceto cracksof panels.

5. ACKNOWLEDGMENTS

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6. REFERENCES

Ferrari, V.J., Hanai, J.B.D., Souza, R.A.D. (2013). “Flexural strengthening of reinforcement concrete beams using high performance fiber reinforcement cement-based composite (HPFRCC) and carbon fiber reinforced polymers (CFRP).” Constr. Build. Mater., 48, 485-498.

Hussein, M., Kunieda, M., Nakamura, H. (2012). “Strength and ductility of RC beams strengthened with steel-reinforced strain hardening cementitious composites.” Cement. Concr. Compos., 34(9), 1061–1066.

Martinola, G., Meda, A., Plizzari, G.A., Rinaldi, Z. (2010).“Strengthening and repair of RC beams with fiber reinforced concrete.”Cement. Concr. Compos.,32(9), 731-739.

Ruano, G., Isla, F., Pedraza R. I., Sfer, D., Luccioni, B. (2014). “Shear retrofitting of reinforced concrete beams with steel fiber reinforced concrete.” Constr Build Mater, 54, 646–658.

Thomas, J., and Ramaswamy, A. (2007). “Mechanical properties of steel fiber-reinforced concrete.” J. Mater. Civ. Eng., 19(5), 285-392.

Wirojjanapirom, P., Matsumoto, K., Kono, K., Niwa, J. (2013). “Experimental study on shear behavior of RC beams using U-shape UFC permanent formwork with shear keys and bolts.” Journal of Japan Society of Civil Engineers, Ser. E2 (Materials and Concrete Structures), 69(1)