Engineering Solid Mechanics 4 (2016) 53-62

Contents lists available at GrowingScience

Engineering Solid Mechanics

homepage: www.GrowingScience.com/esm

Numerical study of shear wall behavior coupled with HPFRCC beam and diagonal reinforcements

Hamid Reza Ashrafi* **and Peyman Beiranvand**

Technical & engineering faculty, Razi University, Kermanshah, Iran

A R T I C L E I N F O

Article history:
Received 6 September, 2015
Accepted 20 December 2015
Available online
21 December 2015

Keywords:
Shear wall
Diagonal reinforcement
Nonlinear finite element
HPFRCC

A B S T R A C T

High performance fiber-reinforced cementitious composites (HPFRCC) are aggregates like cement grout with fine grains and fibers which can be used in many cases like seismic improvement of building components. One of these building components is connecting beam in coupled shear wall which can increase plasticity and energy absorption. In this paper nonlinear finite element model of coupled beam containing HPFRCC is analyzed and the influence diagonal reinforcement is investigated on cracking patterns, stress contours and hysteresis diagrams of shear wall. It was observed that diagonal reinforcements play significant role in shear load bearing capacity of shear wall coupled with HPFRCC beam.

1. Introduction

Conventional concretes made of Portland cement and natural grains have some shortcoming and drawbacks, and hence specific concretes have been designed and innovated in recent years for reducing such problems. In concrete technology, this class of concretes is called advanced concretes. Conventional concretes usually have various capillary cracks and hence due to rapid development of capillary cracks under imposed stresses, tensile strength of concrete materials is often low. The use of fibers in concrete (i.e. constructing fiber concrete) is an effective way in prevention of micro and macro cracks and increasing the concrete tensile strength. In recent years, significant developments have been achieved for designing and manufacturing of fiber-reinforced cementituos composites (FRCC). Most of the previous studies in this field are related to developments of grout, manufacturing different types of fibers, grout-fiber interaction, composite production process, main mechanisms for controlling behavior of FRCC composite and continuous improvement of executive costs. With more developments in concrete technology, high-performance fibers was introduced. The term “high-performance” refers to a specific class of fiber concretes which have strain hardening behavior under

* Corresponding author.
E-mail addresses: h.r.ashrafi@razi.ac.ir (H. R. Ashrafi)

doi: 10.5267/j.esm.2015.12.004

stress after first cracking along with formation of multiple cracks and high strains. Using high-performance aggregates instead of conventional aggregates is an interesting research subject and various studies have been conducted in this field. These aggregates, in addition to increasing the capacity of the structures against earthquake loads, can help the sustainability of the structures against harmful environmental factors. One of these high-performance composites (which has significant development in recent years), is high-performance fiber-reinforced cement composites (Parra-Montesinos, 2005; Canbolat et al., 2005; Tran et al., 2014).

Concrete shear walls are one of the resistant systems against earthquake which are frequently used due to their suitable performance in previous earthquakes. Because of using elevator in tall buildings, shear walls located around the stairs should have openings. In this case, two shear walls (called coupled shear walls or correlated walls) are designed with connecting beams. It is well understood that that maximum shear stress in a bending beam with rectangular cross-section develops along the neutral axis. Coupled shear wall is like vertical console beam and if it is weak in neutral axis, failure will occur as slip in the vertical shear. Regarding this explanation, it is expected that connecting beams exhibit significant deformation during earthquake. They are also used as basic energy dissipating components. Most previous studies on the deep connecting beams were concentrated on innovation of suitable methods for enough plasticity and reduction in reinforcements.

Since establishing diagonal reinforcements in connecting beams is a difficult process, using high performance FRCC (HPFRCC) can be a solution for reduction or elimination of these reinforcements and spirals. HPFRCCs, with strain hardening response in direct stress, with increase in the number of micro-cracks, show higher plasticity than common concretes. Therefore, when structural elements are subjected to the seismic forces, HPFRCCs can improve the energy dissipation by bridging the fibers on the micro-cracks and also by creating suitable cohesion between reinforcements and cement composites. During past decade, empirical researches have shown that HPFRCC aggregates are effective in the improvement of seismic performance like plasticity, energy dissipation, destruction control and etc. Application of bending frame system as a resistant element against lateral forces, especially seismic forces, needs certain requirements which meet the plasticity of the frame. These details are difficult to implement and their good construction is ensured only under high quality control at workshop.

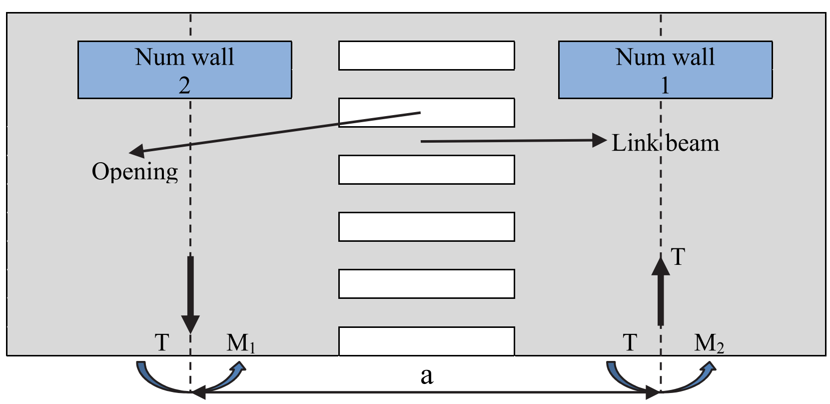

Fig. 1. Schematic of coupled shear wall and the developed forces in coupled shear walls.

Observation of the performance of solid bending frames and buildings with shear-walls in recent earthquakes indicates confident behavior of second-type structures against earthquake. Shear wall are stiffer compared to solid frames in building performance and therefore, it is expected that they bear large lateral forces during earthquake. In contrary, lateral displacement of buildings with shear wall is lower than solid frames. Since shear walls have suitable stiffness among different resistant systems against lateral forces, their application and design has been increased in the tall building, due to considering several vertical opening (such as window, door and left). In such cases we can use coupled shear walls, in which two or several separated shear walls are connected by means of connecting beams to each other. Benefits of using coupled shear wall are: (i) high efficiency against lateral loads (ii) optimal design relative to separated shear wall (iii) plasticity and high energy absorption characteristics and (iv) secondary defense against lateral loads. This collection forms a coupled shear wall and connecting beam is called coupled beam. A schematic representation of coupled shear wall is shown in Fig. 1. Several researchers have studied the behavior of shear walls in the past years. Paulay (2002) analyzed a shear wall system and concluded that excellent displacement control provides a strong coupled system by using slender walls with endangering relative displacements of floors. He stated that displacement limits during plastic response is not influenced by upper dynamic modes, and by correct reinforcement of walls, the larger hysteresis damping could be achieved relative to traditional systems. Paulay has studied the behavior of concrete shear wall with openings, while there is a need to identify the performance of shear wall with opening including all basic components and connecting beams in compound and integrated from in non-elastic limit in order that engineering community reaches to a general view of the behavior of these structures under severe earthquakes.

Zhao et al. (2004) studied the effect of connecting beam height on its nonlinear behavior and showed that by increasing the height of connecting beam shear behavior becomes dominant. They also investigated types of break-out on connecting beams and concluded that bending cracks form in the tensile corners of connecting beam to the wall and shear diagonal cracks are created near the center which can lead to break-out of connecting beam. They observed that, bending cracks initiate in the beam to wall connection place and then gradually open upward and cause large local rotations in the place of connections. By further applying the loads they extend toward tensile zone until only one-fourth of beam remains intact. Consequently, a low effective cross-section remains to resist against shear which increases ship-shear break-out (Zhao et al. 2004). They also pointed out although adding shear reinforcement can increase the shear strengths and prevent shear-tensile break-out, but it may lead to shear-slip break-out which is brittle break-out.

Kim and Lee (2003) tried to develop finite element method for analyzing shear walls. They considered rotational degrees of freedom and analyzed the concrete shear walls with opening with three different ratios for width and height of opening. They concluded that in the case of small openings, 4-node elements without rotational freedom of nodes, provide lateral displacements but the error of this mesh is high for large openings. Tjhin et al. (2007) conducted nonlinear static and dynamic analysis and time-series of 6-floor building with concrete shear wall by using DRAIN-2DX software and studied their performance levels. Bessason and Thordur (2002) studied the shear-wall equipped buildings with opening in Tjornes Fracture seismic area in North Iceland and modelled them with ANSYS software and soild65 element. They modelled short shear walls with opening and by different reinforcement ratios and considered the effect of structure roof in their modeling and concluded that change in the reinforcements has strong effect on their capacity curve. Their research showed that cracks are developed with different reinforcement ratios in the same shear but in walls with low reinforcement after formation of first cracks, these cracks can open and break the shear wall. But in the walls with suitable reinforcements, cracks cannot open and this may increase their plasticity. However, they did not model the nonlinear behavior of concrete in shear. In another study, coupled beams fabricated by HPFRCC in Michigan State University was studied by Canbolat and coworkers (2005) under semi-static cyclic loads with displacement control conditions for short coupled-beams. Their results indicated that diagonal reinforcement are needed in order to reach higher displacements and relevant collars can be eliminated. In another works, Lequesne et al. (2010) and Setkit (2012), tested three coupled beams with different length to height ratios and showed that using HPFRCC, increases bending plastic ability and results in high load bearing capacity. Shin et al. (2014) investigated the effect of HPFRCC on the vibration performance of slender coupled beam in South Korea and showed that using HPFRCC improves the cracking pattern, plasticity of diagonal reinforcement and shear destruction in slender coupled beams. In addition, based on their results the trend of reducing stiffness in HPFRCC coupled beam is lower than that of coupled beam constructed by conventional concrete. Safari and Qahremani (2012) concluded that increasing the height of coupled beam (up to %33) will increase the final strength but further increase in the height of coupled beam has no more positive effect in the value of final strength and can reduce the plasticity. Kheirudin et al. (2003) suggested an equation for metal coupled beam and concluded that the presence of metal connecting beam extends cracks in the shear walls which increases the energy absorption and plasticity of concrete.

In this research, first brief description of coupled shear walls and their basic equations are presented. Then conventional and HPFRCC coupled shear wall beams with and without diagonal reinforcements are analyzed numerically using a finite element software and the influence of concrete type on cracking pattern, forces and stress contours is studied.

2. Analysis of Coupled shear wall behavior

If two shear walls connect in a plate with members with joint connection, imposed moments on them are beard by the walls. But if walls are connected with solid walls, they form a compound set and imposed moment is tolerated by two walls by bending around central axis. Therefore, bending stresses will distribute in linear form along with the collection. However in practice, walls are often connected by flexible walls which have a state between joint and solid case. For the stiffer beams, behavior of the structure will be close to the compound cantilever behavior.
When walls are subjected to the lateral loads, ends of connected beams should withstand against rotation and vertical displacements. Bending behavior of walls creates shear in connecting beams and consequently, they impose opposite moments on the wall. Shears create pivotal force in the walls. Therefore, moment caused by lateral load in each layer of the structure (M_e) is tolerated by sum of bending moments of walls in that layer (M_1+M_2) and moment caused by axis force is tolerated (as shown in Fig. 1).

$$\boldsymbol{M_e = M_1 + M_2 + T.a} \tag{1}$$

In Eq. (1), T.a is inverse moment caused by bending of connecting beams which resists against free bending of walls. This value is zero for walls with joint connections and is maximum when connecting beams are solid. Differential equation governing on the coupled shear wall is

$$\boldsymbol{\frac{d^2T}{dy^2} - \alpha^2 T = -\gamma M_e} \, . \tag{2}$$

In Eq. (20, T is axis force and M_e is external moment. Value of α^2 is obtained by following equation:

$$\boldsymbol{\alpha^2 = \frac{12I_b}{C^3h}\left[\frac{a^2}{I_1+I_2} + \left(\frac{1}{A_1}+\frac{1}{A_2}\right)\right]} \tag{3}$$

where *c* is free span of beams. We also have:

$$\boldsymbol{\frac{1}{K} = \frac{\gamma a}{\alpha^2}} \, , \tag{4}$$

where *K* is obtained by following equation:

$$\boldsymbol{K = 1 + \frac{I_1+I_2}{a^2}\left(\frac{1}{A_1}+\frac{1}{A_2}\right)} \tag{5}$$

$$\gamma = \frac{12aI_p}{C^3h(I_1 + I_2)} \tag{6}$$

3. Finite element modelling

In practical applications, numerical design codes and finite element software are powerful tools for analyzing complex structures. In this research, we have conducted numerical study of shear wall coupled beam with HPFRCCC by conventional concrete using VECTOR2 software. VECTOR2 is nonlinear finite element software which is only used for modelling concrete members. In this software, crack behavior is considered as orthotropic material and based on the any of following assumptions:

1-Modified Compression Field Theory (MCFT)

2-Disturbed Stress Field Model (DSFM)

MCFT method is based on this principle that basic stress and strain angles are the same. In cases without slip or rotation in the main angles, this method overestimates the compressive softening of concrete during transverse compression. But DSFM model can take into account slip during cracking and concrete compressive softening. In order to calculate the depth of beams, we considered the ratio of shear span to effective depth (a/d) equal to 2. Three different samples (described in Table 1) were studied with different types of concrete and diagonal reinforcements. Also characteristics of the investigated concretes are presented in Table 2.

Table 1
Characteristics of shear wall coupled beam sample

Sample	a/d ratio	Diagonal reinforcement	Type of concrete
1	2	No	HPFRCC
2	2	No	HPFRCC
3	2	Yes	Conventional concrete

Table 2
Characteristic and properties of samples used in numerical models

Type of concrete	Place of concrete	Compressive strength (MPa)	Thickness (mm)	Rod diameter (mm)	Angle to axis X	Reinforcement percent	Steel yield stress (MPa)	Steel final stress (MPa)
1	Coupled beam	62	200	8 mm 12 mm 12 mm	0 75 100	1 1	240	370
2	Coupled beam (HPFRC) without diagonal reinforcement	68	200	10 mm	0	1.5	240	370
3	Coupled beam (HPFRC) with diagonal reinforcement	68	200	8 mm 12 mm 12 mm	0 75 100	1 1 1	240	370
4	Concrete block	34	500	12 mm 10 mm	0 90	3 3	240	370
5	Link to prevent rotation of wall	0.5	500	-	-	-	-	-

4. Results of numerical analysis

In this section, we will study the models for crack distribution pattern, maximum crack width, hysteresis diagrams, distribution of stress in different cross-sections, average stress of reinforcements in concrete, moments in beginning and end of beam, axis and shear force in different drifts. In fact, the role of HPFRCC in eliminating diagonal reinforcements is examined and emphasized by modeling deep beams with length to span ratio of 2. In order to prevent rotation of shear walls, high strength links were considered in the numerical analyses. In the following, obtained numerical results are presented and discussed for different types of coupled beams.

4.1. Response of HPFRCC coupled beams without diagonal reinforcement

Fig. 2 shows the numerical model of a coupled beam for HPFRCC without diagonal reinforcement and the created crack pattern in this system. Maximum crack width in rupture of this coupled beam was obtained about 5.39 which shows the role of diagonal reinforcements in reduction and distribution of crack width. The hysteresis diagram of this type of coupled beam without diagonal reinforcement has been presented in Fig. 3. Table 3 also presents the computed forces and moments for this type of concrete with different drifts. Contours of concrete strength and average stress for HPFRCC without diagonal reinforcement have been also presented in Figs. (4-5) respectively.

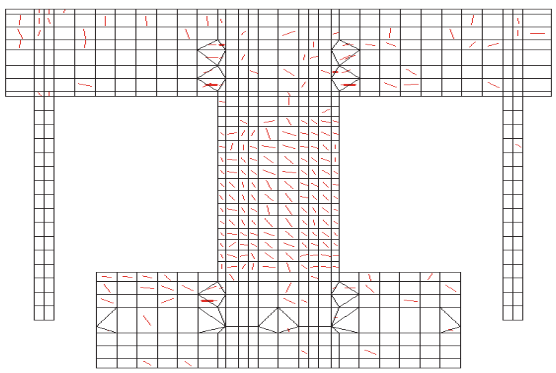

Fig. 2. Crack pattern in HPFRCC without diagonal reinforcement

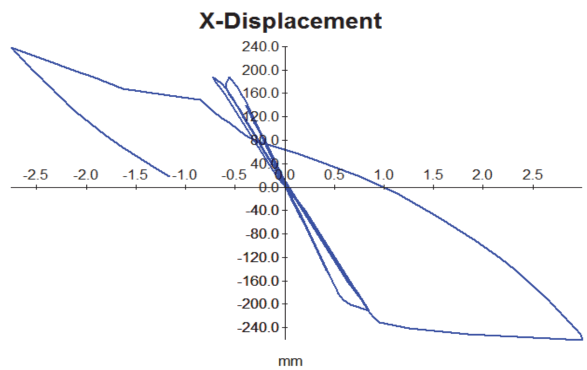

Fig. 3. HPFRCC hysteresis diagram without reinforcement

Table 3
Forces in coupled beam (type 1)

Drift	Axis force (kN)	Shear force(kN)	Beam moment (kN.m)
3%	247	259	3
2.5%	205	120	4.9
2%	164	60	6
1.5%	140	20	55

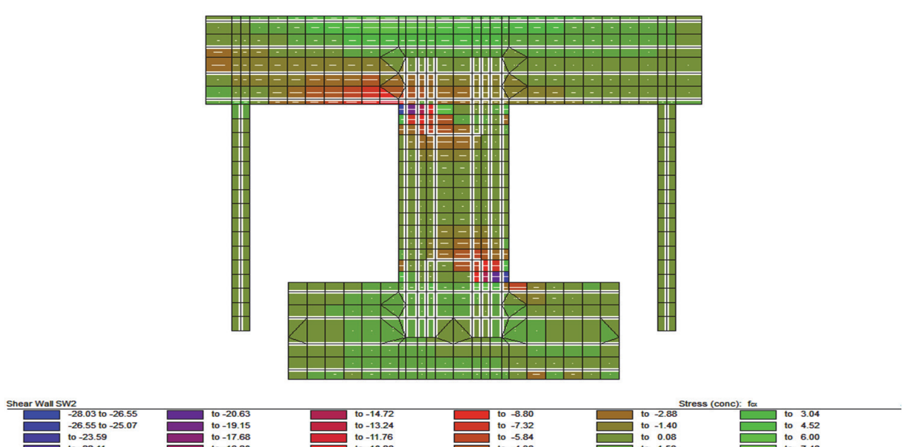

Fig. 4. Concrete stress (f_c) in cross-section with HPFRCC concrete without reinforcement

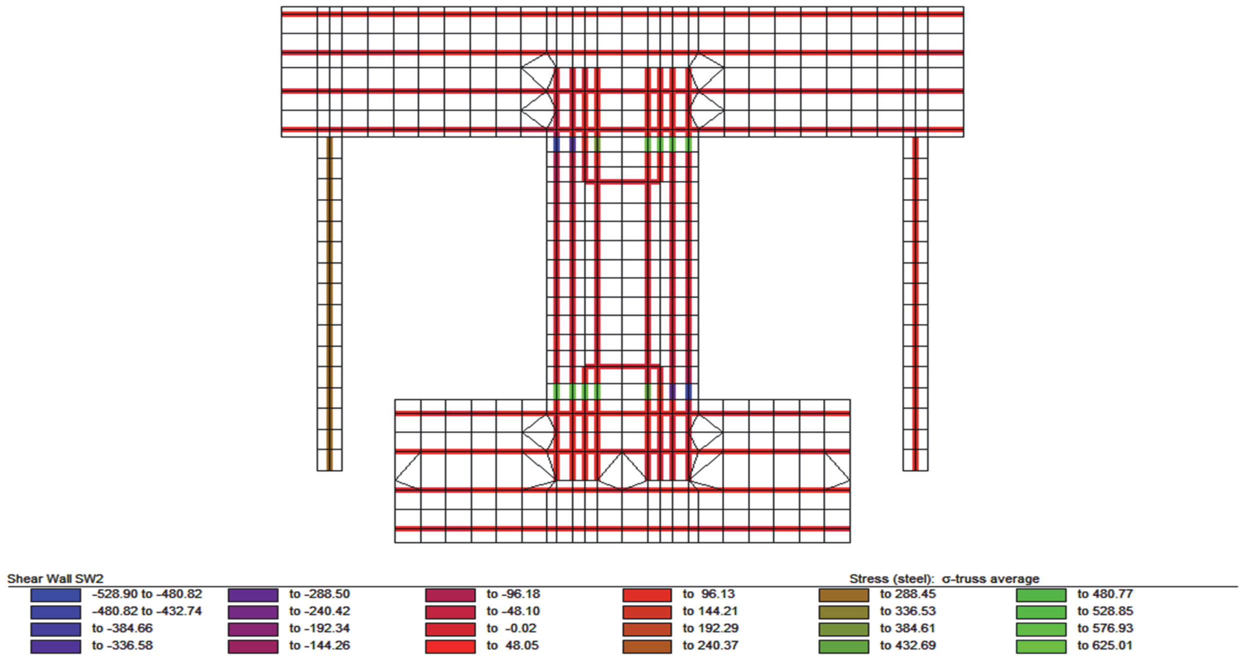

Fig. 5. Average stress of reinforcements in HPFRCC without diagonal reinforcements.

4.2. Response of HPFRCC coupled beams with diagonal reinforcements

Fig. 6 shows the crack pattern in a HPFRCC concrete containing diagonal reinforcement in which the maximum crack width in rupture is determined 1.4 mm. The hysteresis diagram and the force data of this type of coupled beam has been presented in Fig. 7 and Table 3, respectively. The corresponding stress contours of HPFRCC coupled beams with diagonal reinforcements have been also presented in Figs. 8 and 9, respectively.

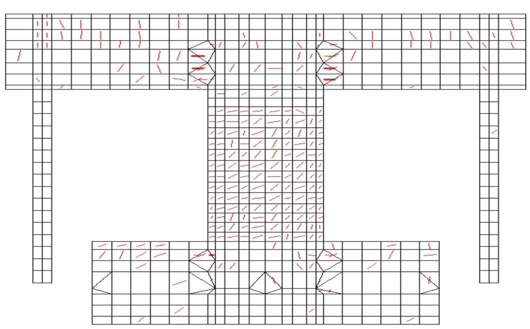

Fig. 6. Crack pattern in HPFRCC with diagonal reinforcements

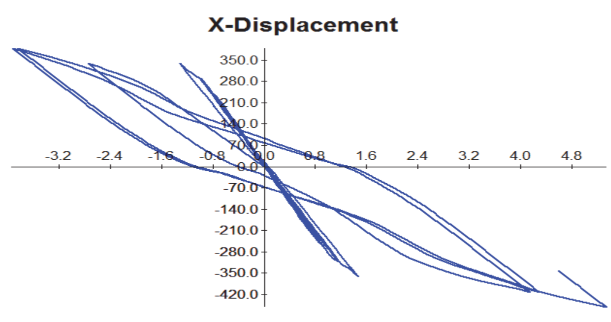

Fig. 7. HPFRCC hysteresis diagram with diagonal reinforcement

Table 4
Forces in coupled beam (type 2)

Drift	Axis force (kN)	Shear force(kN)	Beam moment (kN.m)
3%	417.7	445.3	9
2.5%	298	458.6	4.4
2%	279	379.9	12
1.5%	260.2	157	26

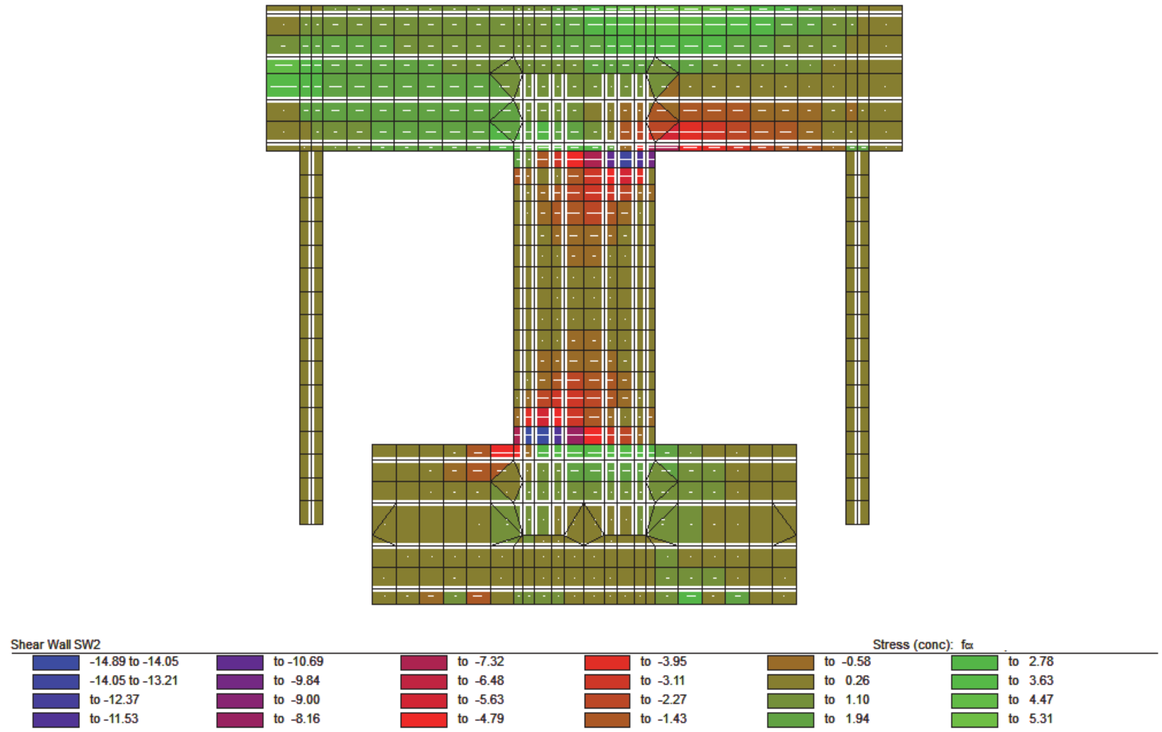

Fig. 8. Concrete stress (f_c) in cross-section with HPFRCC concrete with diagonal reinforcement

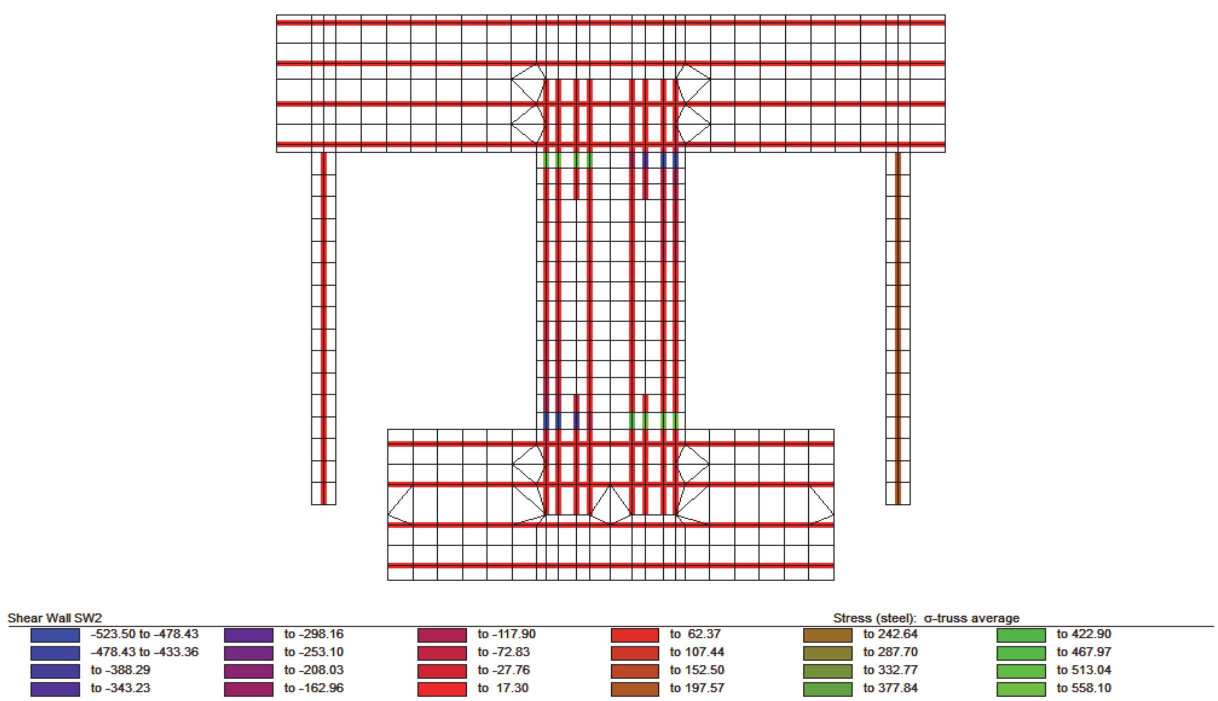

Fig. 9. Mean stress of reinforcements in HPFRCC samples with diagonal reinforcement.

4.3. Response of coupled beam conventional concrete with diagonal reinforcement

The finite element results obtained for this type of shear wall coupled beam have been presented in Figs. (10-13) and Table 6. In this case, maximum crack width in rupture was determined about 1.46 mm.

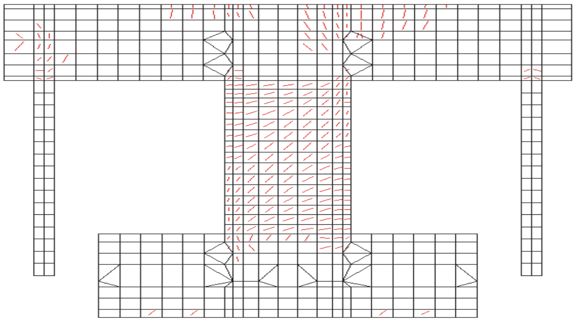

Fig. 10. Crack pattern in conventional concrete with diagonal reinforcement

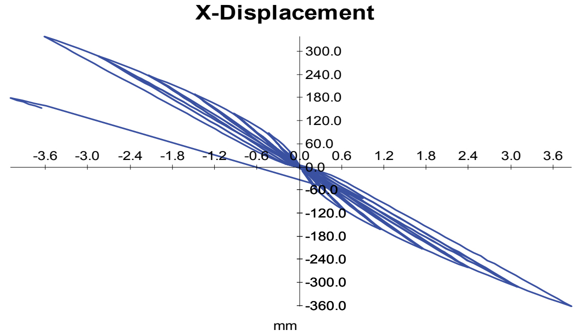

Fig. 11. Hysteresis diagram for conventional concrete with diagonal reinforcement

Table 6
Forces in coupled beam (type 3)

Drift	Axis force (kN)	Shear force(kN)	Beam moment (kN.m)
3%	916	330	200
2.5%	217	339	193
2%	164	250	140
1.5%	120	220	127

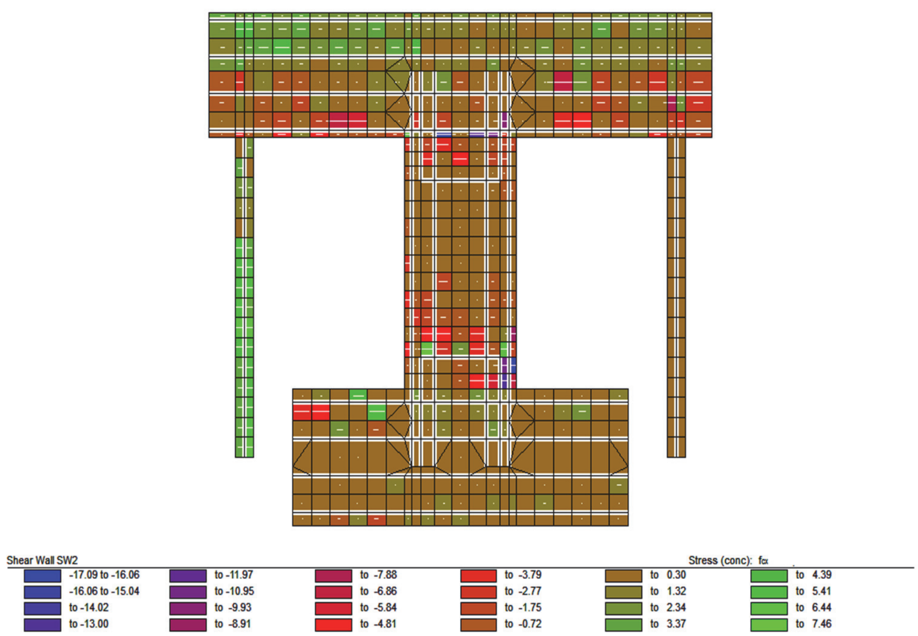

Fig. 12. Concrete stress in cross-section with conventional concrete with diagonal reinforcement

5. Conclusion

1. In HPFRCC beam with diagonal reinforcements, the width of cracks in final moment was limited to 1.4mm that shows %30 reduction with respect to the conventional concrete. In these samples, crack distribution was monotonic and capillary.
2. Shear force carried by the HPFRCC sample with diagonal reinforcement was significantly higher than (about 150%) the sample without diagonal reinforcement.
3. Regarding hysteresis diagrams, the highest energy absorption was related to the HPFRCC sample with diagonal reinforcement.

4. Diagonal reinforcement reduces stresses in the coupled beam and increases longitudinal reinforcement which results in higher capacity of beam.

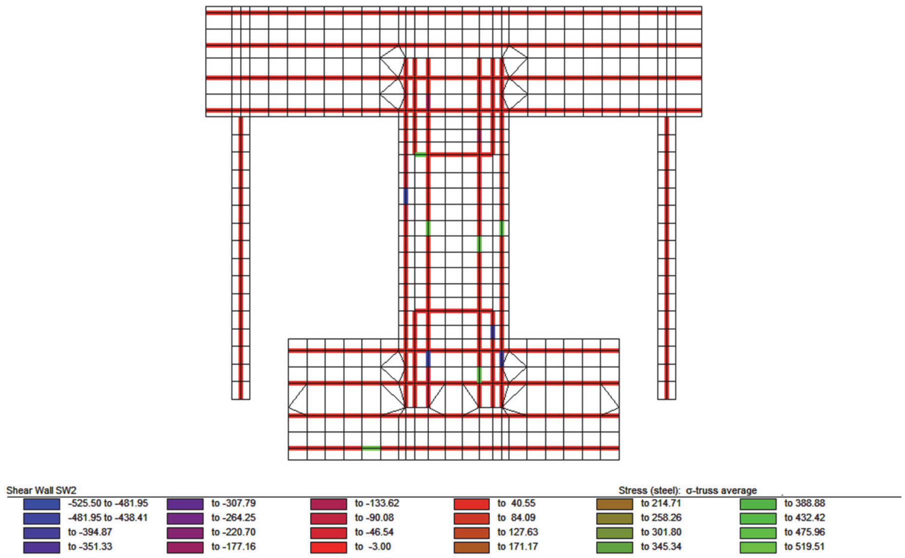

Fig. 13. Mean stress of reinforcement in concrete with diagonal reinforcement

References

Bessason, B., & Thordur, S. (2002). Capacity and earthquake response analysis of RC-shear walls. *Nordic Concrete Research Publications*, *27*, 1-14.

Canbolat, B. A., Parra-Montesinos, G. J., & Wight, J. K. (2005). Experimental study on seismic behavior of high-performance fiber-reinforced cement composite coupling beams. *ACI Structural Journal*, *102*(1).

Khierudin, A. Fereidoon, A., & Mahzarnia, S. H. (2003). Calculation of pinned beam length and enhancement in coupled shear walls. 6th international civil engineering conference, Isfahan, Iran

Kim, H. S., & Lee, D. G. (2003). Analysis of shear wall with openings using super elements. *Engineering Structures*, *25*(8), 981-991.

Lequesne, R., Setkit, M., Parra-Montesinos, G. J., & Wight, J. K. (2010). Seismic Detailing and Behavior of Coupling Beams with High-Performance Fiber-Reinforced Concrete. *Special Publication*, *272*, 189-204.

Parra-Montesinos, G. J. (2005). High-performance fiber-reinforced cement composites: an alternative for seismic design of structures. *ACI Structural Journal*, *102*(5), 668.

Paulay, T. (2002). The displacement capacity of reinforced concrete coupled walls. *Engineering Structures*, *24*(9), 1165-1175.

Saffari, H., Qahramani, K. (2012). The study of steel arrangement in final strength and forming of reinforced coupled shear walls. Islamic Azad University, Kerman, Iran.

Shin, M., Gwon, S. W., Lee, K., Han, S. W., & Jo, Y. W. (2014). Effectiveness of high performance fiber-reinforced cement composites in slender coupling beams. *Construction and Building Materials*, *68*, 476-490.

Setkit, M. (2012). *Seismic behavior of slender coupling beams constructed with high-performance fiber-reinforced concrete* (Doctoral dissertation, The University of Michigan).

Tjhin, T. N., Aschheim, M. A., & Wallace, J. W. (2007). Yield displacement-based seismic design of RC wall buildings. *Engineering Structures*, *29*(11), 2946-2959.

Tran, T. K., & Kim, D. J. (2014). High strain rate effects on direct tensile behavior of high performance fiber reinforced cementitious composites. *Cement and Concrete Composites*, *45*, 186-200.

Zhao, Z. Z., Kwan, A. K. H., & He, X. G. (2004). Nonlinear finite element analysis of deep reinforced concrete coupling beams. *Engineering Structures*, *26*(1), 13-25.