Influence of Double Idealized Shear Flow Zones on Torsional Resistance of High Strength Fibrous Concrete Beams

Karim, F.R.[1], Abu Bakar, B.H.[2], Kok Keong, Choong [3], Aziz, O.Q.[4]

Abstract-- **This study highlights the effect of additional reinforcements in the idealized core zone of fibrous high strength concrete beams for resisting pure torsional loading. The transverse and longitudinal reinforcements were added in the area considered as idealized core zone which is supposed to be in tension condition plus the traditional reinforcements located in the main idealized shear flow zone. Four fibrous high strength under-reinforced concrete solid beams were cast and tested under pure torsion to verify the influence of secondary shear flow zone on the torsional resistance. The tested beams were designed according to ACI318-14. The transverse and longitudinal reinforcements were kept constant in the idealized main shear flow zone while the covered area in the idealized core zone by reinforcements was added as a different percentage of this zone. The test results show that torsional resistance at peak load and torsional resistance provided by reinforcement and fibre were improved up to 14.18% and 146%, respectively, due to covering of 85.4% of the idealized core zone area by transverse and longitudinal reinforcements. In addition, due to contribution of reinforcement in the idealized core zone, the strains in transverse and longitudinal reinforcements were reduced up to 60% and 69.4%, respectively.**

Index Term**— Fibrous high strength concrete, Idealized core zone, Pure torsion, and Secondary shear flow zone.**

I. Introduction

In space truss analogy theory, the solid concrete section behaves as a thin-walled tube. The thin-walled tube produces idealized shear flow zone and the area inside of the tube is considered as idealized tension zone[1, 2]. In space truss model, the idealized core zone is considered not to be contributing to torsional resistance due to the reason that it is subjected to tension and concrete is weak for carrying tension [3-8]. However, fibrous high strength concrete has higher tensile strength than the non-fibrous high strength concrete [9-13].

In space truss analogy, there are two elements. The first one is the reinforcements which carry tension stress and the second element is concrete which carry compression stress. In order to make the theory works well in the whole section for resisting torsion, the presence area behind idealized shear flow zone should heed by adding element to carry tension and the fibrous concrete is going to carry compression as a result. The two idealized shear flow zones improved torsional resistance and eliminated the effect of tension stiffening for the reinforcement in the main idealized shear flow zone[14, 15].

II. Research Significance

The effect of additional reinforcements in the idealized core zone area to enhance torsional resistance, twisting angle, and the strain in concrete and reinforcements are highlighted in this paper. Even though around 40% of solid section area behind of idealized shear flow zone area was ignored for resisting torsional moment, the majority of the fibrous concrete section could contribute torsional resistance from additional transverse and longitudinal reinforcements in the idealized tension zone.

III. Experimental Works

To activate the idealized core zone, four under-reinforced fibrous high strength concrete beams were cast. (B-1-H) is a control beam and the remaining fibrous concrete beams (B-2-H, B-3-H and B-4-H) contained transverse and longitudinal reinforcements in the idealized tension zone. The ratio of area covered by reinforcements in the idealized tension zone was varied from 0 to 0.854 at post cracking stage. While the clear span to depth ratio and the height to width ratio of the beam section were kept constant. The beam dimensions are tabulated in Table 1. The pure torsion was applied on the main beams from two patch loads acting on the arms of the beam which were transferred to main beam as a torsional moment.

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First Author – Karim, F.R., PhD Candidate, School of Civil Engineering, Universiti Sains Malaysia, Pulau Pinang, Malaysia, email: f1974e1997m2004@yahoo.com, Phone:+60-(0)111-451-39-13 (Corresponding Author)
Second Author – Abu Bakar, B.H., Professor, School of Civil Engineering, Universiti Sains Malaysia, Pulau Pinang, Malaysia, email: cebad@usm.my.
Third Author – Kok Keong, Choong, Associate Professor, School of Civil Engineering, Universiti Sains Malaysia, Pulau Pinang, Malaysia, email: cekkc@usm.my.
Fourth Author – Aziz, O.Q., Professor, Civil Engineering Department, College of Engineering, Salahaddin University, Erbil, Iraq and email : omerqarani@gmail.com.

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TABLE I
MEASURED DIMENSIONS OF THE FIBROUS HIGH STRENGTH CONCRETE BEAMS

Beam denotation	Width, mm	Height, mm	Span length, mm
B-1-H	228	278	1584
B-2-H	220	270	1560
B-3-H	220	270	1552
B-4-H	222	272	1564

MATERIALS, MIX PROPORTIONS AND SPECIMEN PREPARATION

A. *Materials and mix proportion*

The target compressive strength of the fibrous high strength concrete was 55 MPa. Type I ordinary Portland cement (Tasik brand) was used. Granite crushed stone 10 mm maximum size, silica sand, filtered tap water, HRWR Sika VC2199, PLastiment R retarder with copper coated micro steel fibre were used for producing fibrous high strength concrete. After adjustments between these materials, the final mix proportion for casting with high workability and required strength is shown in Table II

TABLE II
MIX PROPORTION OF FIBROUS HIGH STRENGTH CONCRETE

Materials	Quality, kg/m^3
Cement (Type I)	511.1
Silica sand	680.55
Crushed stone	833.33
Water	207
Super-plasticizer VC2199	10.22
Retarder-admixture (Plastiment R)	2.55
Micro steel fibre A (21mm X 0.35 mmΦ)	21.59
Micro steel fibre B (12 mm X 0.2 mmΦ)	64.76
Slump, mm	190

Φ: diameter of fibre, mm

B. Preparation of beam specimens

The main longitudinal reinforcements in the idealized shear flow zone were 4-12mm diameter bars placed at corners of the stirrup. Transverse reinforcement was provided at 95 mm spacing which has 6 mm diameter in two-leg rectangular form 166 mm wide and 216 mm depth with 135º standard hooks as shown in Fig.1. The details of the reinforcements in the idealized core zone are shown in Fig. 2.

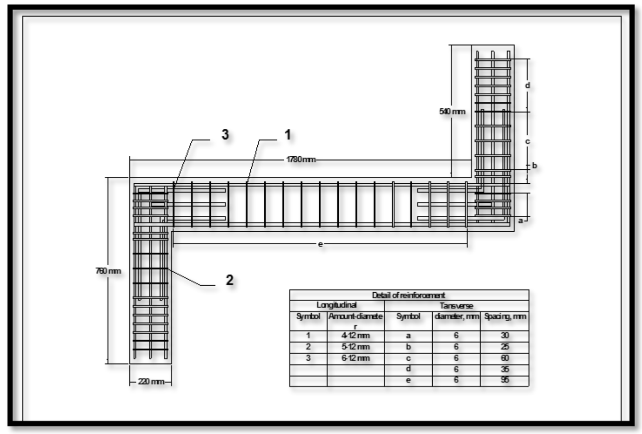


Fig. 1. Detail of reinforcements in the fibrous concrete beam B-1-H

C. Fabrication of specimens

Two pan mixer with 0.05 m^3 capacity were used to cast fibrous high strength concrete beams which with the casting of 3 cubes, 3 cylinders, 3 prisms and 6 cubes for bond test between reinforcement and fibrous concrete [16-19]. For production of fibrous high strength concrete, the following sequence for mixing of ingredients was followed. Granite crushed stone and silica sand were mixed continuously for 90 seconds. Next, the Portland cement was added to the mixed materials. Then, the whole mixing tap water blended with high range water reducer were added to the blended materials for 30 seconds. After that, retarder (Plastiment R) was added to the mix to delay setting time in 30 seconds. Copper coated steel fibre was included to the blended materials which was passed through the steel wire mesh for 180 seconds.

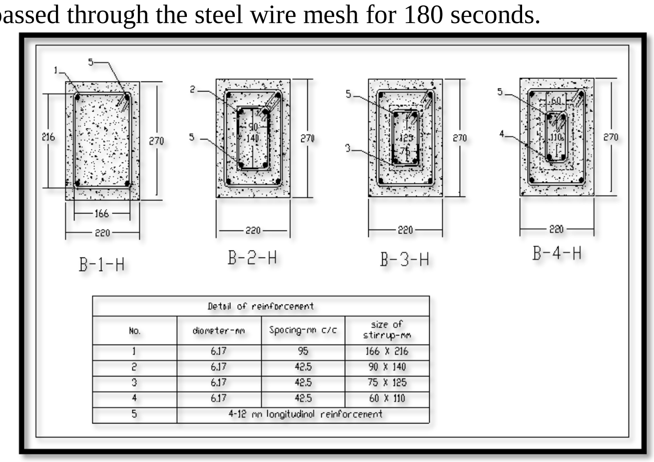


Fig. 2. Detail of reinforcements in the idealized core zone

The mixing process was continued for another 120 seconds to verify that the fibre was uniformly distributed. Then, the fresh concrete was cast in 4 layers inside of plywood mould and each layer was vibrated for 45 seconds along the entire length of the beam. Next, the fibrous concrete was left in the mould for 24 ± 2 hours. Then, it was removed from the mould and covered with burlap. Wet curing method was used until 28 days age of concrete.

TESTING OF FIBROUS HIGH STRENGTH CONCRETE BEAMS

The specimen was placed on two saddle supports. The load was applied using test set-up with capacity of 500 kN capacity in the heavy structure laboratory of the School of Civil Engineering, Universiti Sains Malaysia. The load passed through the load spreader beam to the ends of loading arms. The bending moment in the loading arms was converted to pure torsion in the main beam as shown in Fig.3 and 4. The load was applied manually up until the main beam failed under pure torsional loading. The twisting angle, shear strain in concrete and strain in reinforcements were measured by LVDTs and electrical strain gauges. However, the twisting angle was measured from frame which was clamped on the section of the beam and displacement was measured by LVDTs on both sides of the frame as shown in Fig. 5.

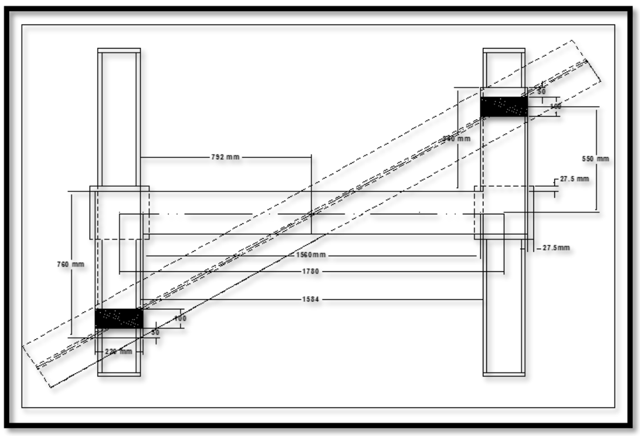


Fig. 3. Schematic Test set-up

Fig. 4. Experimental set-up of the beams

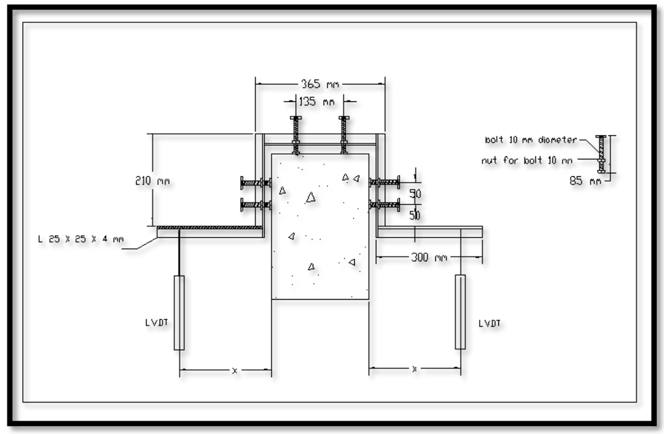


Fig. 5. Schematic measuring of twisting angle

IV. RESULTS AND DISCUSSIONS

The mechanical properties of fibrous high strength concrete used for casting beams were measured as shown in Table 3. In addition to the properties, the value of torsional resistance and twisting angle were measured at crack and peak loads as tabulated in Table 4.

TABLE III

MEASURED PROPERTIES OF FIBROUS HIGH STRENGTH CONCRETE BEAMS

Beam denotation	fc', MPa	f_{sp}, MPa	f_r, MPa	Bond strength, MPa	
				f_{bt}	f_{bL}
B-1-H	62.10	8.71	8.51	4.87	10.72
B-2-H	47.81	6.66	6.32	5.09	10.54
B-3-H	56.31	8.92	8.35	5.00	11.37
B-4-H	53.22	7.36	7.47	4.85	11.14

TABLE IV
RESULTS OF PURE TORSION TEST IN FIBROUS HIGH STRENGTH CONCRETE BEAMS

Beam denotation	T_{cr}, kN.m	Φ_{cr}, rad/m, X 10^{-6}	T_u, kN.m	Φ_u, rad/m, X 10^{-6}
B-1-H	21.08	1606	26.91	11328
B-2-H	16.38	1681	30.73	16270
B-3-H	18.94	1538	28.37	14020
B-4-H	18.76	2225	28.13	20598

A. TORSIONAL MOMENT

The additional reinforcements in the idealized tension zone improved the torsional resistance at peak load and torsional resistance provided by reinforcements and fibre up to 14.18% and 146%, respectively. In fact, the torsional resistance was improved due to thickening of idealized shear flow zone which combined between main and secondary idealized shear flow zones as shown in Fig. 6 and 7. In contrast, the cracking torsional moment was not affected by additional reinforcement in the idealized core zone because it was influenced proportionally by the value of compressive strength as shown in Fig. 8.

B. TWISTING ANGLE

The additional reinforcements in the idealized core zone area enhanced the flexibility of the main beams and the function of transverse and longitudinal reinforcements for resisting torsion. In addition, the twisting angle of the beam under pure torsion is affected by stiffness of the section. Therefore, the twisting angle at crack and peak loads increased up to 4.67% and 81.8%, respectively, as shown in Fig. 9.

C. STRAIN IN CONCRETE AND REINFORCEMENTS

The shear strain in fibrous concrete was measured during pure torsional loading as shown in Fig. 10. It was obvious that the value of shear strain was influenced by decrease of idealized tension zone area. The value of shear strain was enhanced up to 116.2% at peak load. In contrast, the reinforcement strain shows different behavior. In fact, the strain in reinforcement which was placed in the area of idealized main shear flow zone was reduced up to 69.4% and 60% in longitudinal and transverse reinforcements, respectively. The strain in reinforcements located in secondary idealized shear flow zones was improved which lead to enhancement of the torsional resistance as shown in Fig. 11-14.

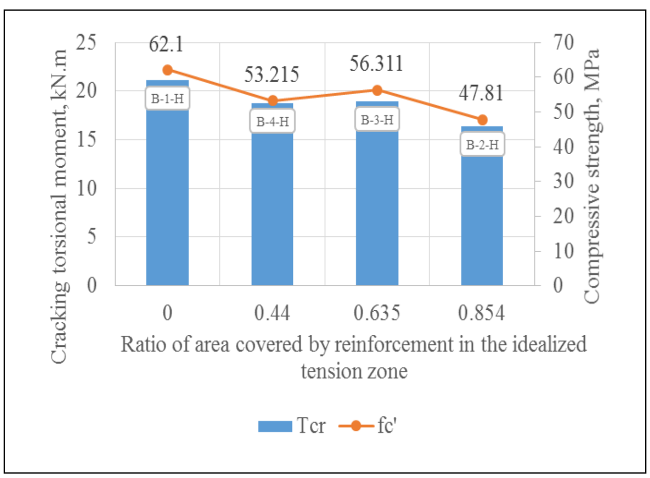


Fig. 6. Torsional moment at peak load versus the percentage of idealized tension zone covered by the reinforcements

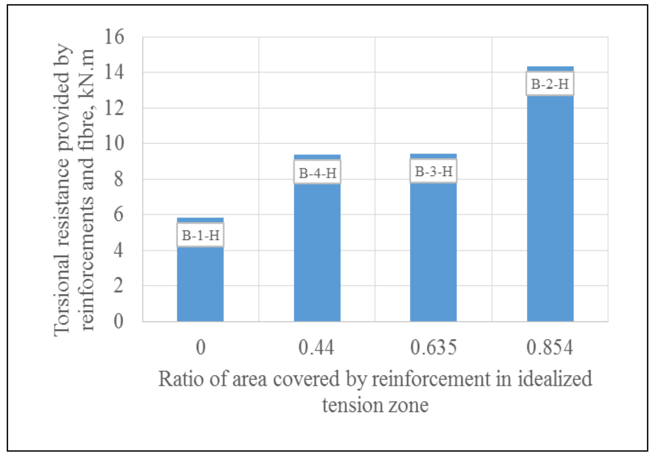


Fig. 7. Torsional moment provided by reinforcement and fibre versus the percentage of idealized tension zone covered by the reinforcements

D. CRACKING PATTERNS

The details of spiral cracks are influenced by additional reinforcements in the idealized core zone such as number of cracks, spacing between spiral cracks and inclination angle of crack at failure as shown in Table 5. The propagation and final pattern of crack with associated loads were recorded next to the crack on the surface of the beam as shown in Fig. 15.

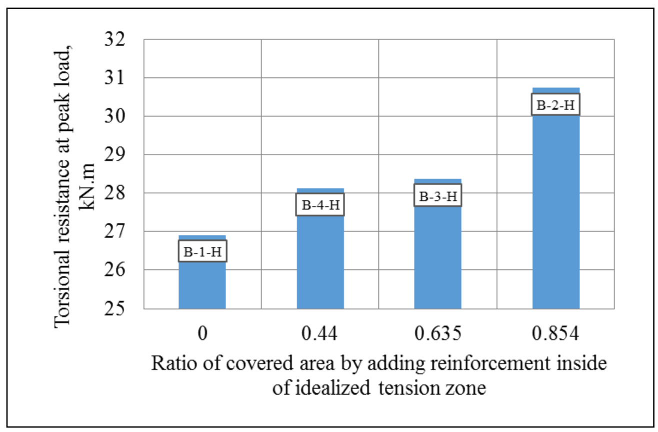


Fig. 8. Torsional moment at crack load versus the percentage of idealized tension zone covered by the reinforcements

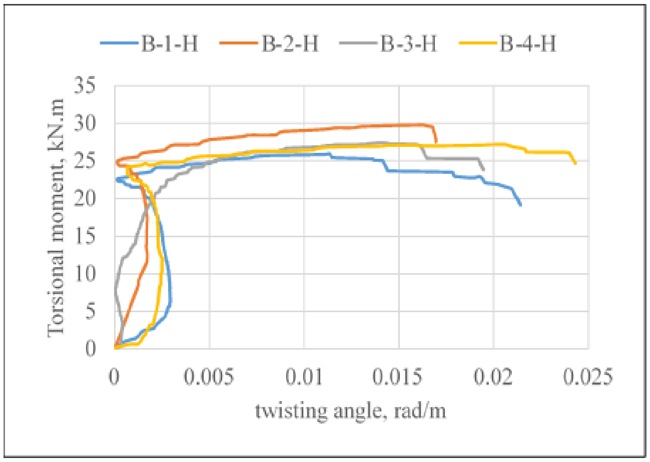


Fig. 9. Torsional moment versus twisting angle

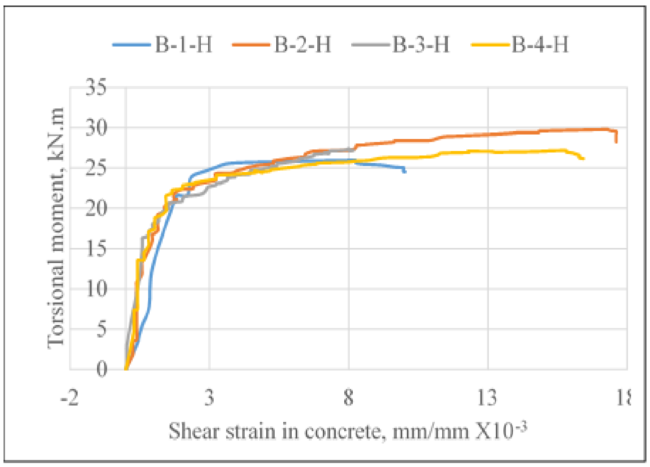


Fig. 10. Torsional moment versus shear strain in concrete

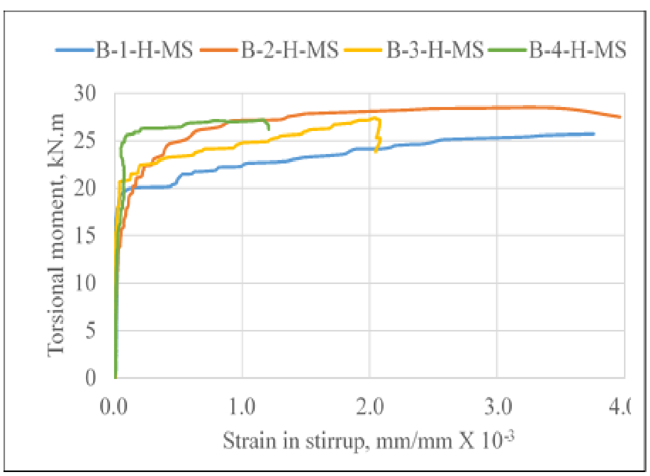


Fig. 11. Torsional moment versus strain in main stirrups

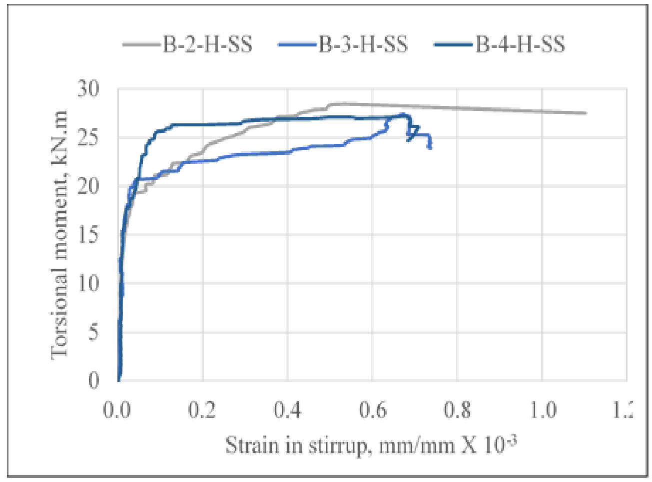


Fig. 12. Torsional moment versus strain in stirrup located in idealized tension zone

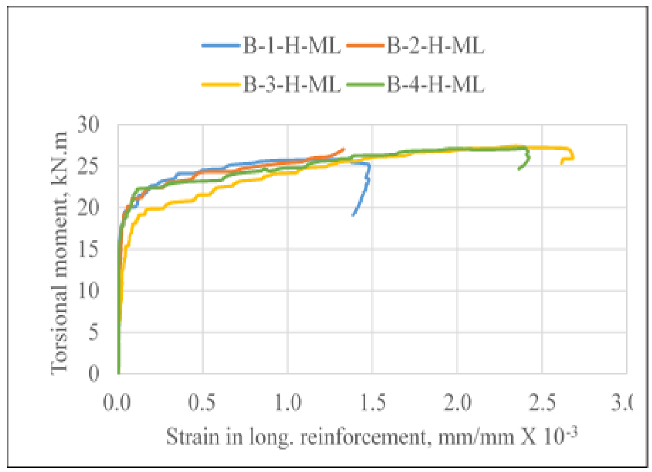


Fig. 13. Torsional moment versus strain in main longitudinal reinforcement

TABLE V
DETAIL OF SPIRAL CRACK OF FIBROUS HIGH STRENGTH CONCRETE BEAMS

Beam denotation	No. of spiral cracks	Θ, degrees	Average spacing between spiral cracks, mm
B-1-H	7	46	178
B-4-H	8	45	201
B-3-H	6	45	292
B-2-H	10	46	171

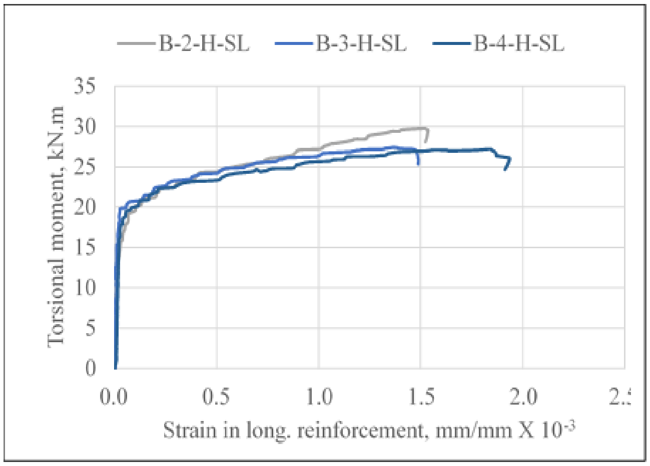
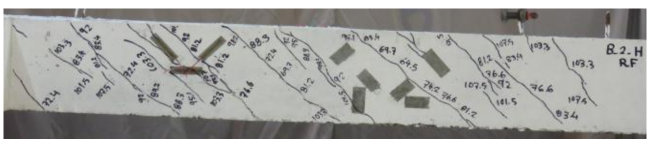
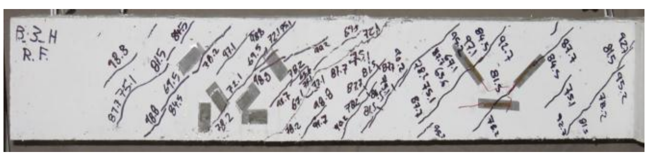


Fig. 14. Torsional moment versus strain in longitudinal reinforcement located in idealized tension zone

B-1-H



B-2-H



B-3-H

B-4-H

Fig. 15. Side view of beams at failure

V. CONCLUSIONS

The following conclusions could be drawn from the test results and modification of space truss analogy theory to include main and secondary idealized shear flow zones:

1. The additional transverse and longitudinal reinforcements in the idealized tension zone covering 85.4% of this zone improved the torsional resistance at peak load and torsional resistance provided by fibre and reinforcements up to 14.18% and 146%, respectively.

2. The additional reinforcements in idealized core zone covering 85.4% of the idealized core zone area by additional reinforcement improved twisting angle and shear strain at peak load 81.8% and 116.2%, respectively. In contrast, the strains in transverse and longitudinal reinforcements were reduced up to 60% and 69.4%, respectively, due to contribution of reinforcements in the idealized core zone to resist torsion.

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Biography:

Karim, F. R. is a research engineer at the Concrete Structures Division. He received his BS from University of Salahaddin, Iraq; and MS from University of Sulaimani, Iraq. His research interests include behaviour and strength of

reinforced concrete beams under combined action and pure torsion and the mechanical properties of concrete.

Abu Bakar, B.H. is a Professor at The School of Civil Engineering, Universiti Sains Malaysia. He obtained PhD from Leeds University, UK and then joined as an academic staff. He has involved in teaching and research for many years and published his works in high impact journals and proceedings. Currently, his area of interest is on Ultra High Performance Fibre Reinforced Concrete and other structural engineering as well.

Kok Keong, Choong is an associate Professor Dr.Choong Kok Keong holds a doctor of engineering degree from The University of Tokyo, Japan. Prior to joining the University, he worked as a research engineer in a company specializing in large span structure. His main research interest is related to computational analysis of shell and spatial structures. He also carried out research study on precast concrete structure.

Omar Qarani Aziz was born in Erbil (Iraq) in 1967. He received the B.S. degree in civil Engineering from the University of Salahaddin (Erbil) in 1990, M.S. and Ph.D. degree in Structural Engineering from the University of Technology (Baghdad) in 1993 and 1997 respectively. He is a faculty member in the Department of Civil Engineering, Salahaddin University since 1993. He is currently Professor in Civil Engineering Department, teaching Design of Reinforced Concrete Structures, author of more than 50 peer-reviewed publications. His research interests include the area of Deep beams, Corbels, fiber concrete, shear of high and ultra-high performance concrete beams and slabs, ultra-high performance concrete, Neural network, punching shear strength of flat plate and flat slabs