Al-Azhar University Civil Engineering Research Magazine (CERM)
Vol. (40) No. (2) April, 2018

EXPERIMENTAL PROGRAM TO STUDY THE SEISMIC BEHAVIOR OF HIGH-STRENGTH CONCRETE EXTERNAL BEAM-COLUMN JOINTS

Heba A. Massoud[1], Ahmed H. Abdelkareem[2], Yehia M. Abd El-Magid[3]

1-Civil Engineer, Al-qalyobeya, Egypt
2- A.Professor of Concrete, Faculty of engineering, Benha University, Al-qalyobeya, Egypt
3- Professor Concrete Structures, Research Institute National Housing and Building Research Centre, Giza, Egypt

ملخص البحث:

في العقود الأخيرة زادت تطبيقات استخدام الخرسانة العالية المقاومة فأصبحت لا تستخدم فقط في المنشآت المائية والكباري ولكن أيضا في المنشآت الشاهقة الارتفاع والمنشآت الجاهزة سابقة التصنيع، وأيضا في الأرصفة. يعد تصميم الوصلات المصنعة من الخرسانة عالية المقاومة في المنشآت الشاهقة مسألة دقيقة وخطيرة نظرا للسلوك القصف في الخرسانة عالية المقاومة مقارنة بالخرسانة العادية. ولكن استخدام وتطبيق معادلات التصميم المتاحة للخرسانة العادية في تصميم الخرسانة عالية المقاومة قد يؤدي الى تصميم غير امن وربما خطورة على المنشأ أو أن يكون التصميم مقيد بشكل غير ملائم. لذا كان لابد من عمل أبحاث لتصميم العناصر المختلفة من الخرسانة عالية المقاومة تصميم أمثل. ويهدف هذا البحث الى دراسة سلوك هذة الوصلات عن طريق الاهتمام بتفاصيل التسليح في منطقة الوصلة لجعل الوصلات أكثر كفاءة في مقاومة الأحمال العرضية المؤثرة عليها.

1. Abstract

This paper presented the experimental investigations performed on external high-strength concrete (HSC) beam-column joints with and without column axial compressive loading. Eight specimens with varying reinforcements within the joint were constructed to model a typical exterior beam-column joint in RC frame building and simulate the inflection points of a frame building. The inflection points were assumed at mid-height of the columns and mid-span of the beams. The specimens were loaded by applying constant compressive axial load on the columns while the free end of the beams were subjected to reversed increasing cyclic displacement in order to simulate seismic effect. The specimens were sorted into three groups based on the concrete compressive strength, the joint reinforcement detailing and the compressive axial load on the column. The first group (Group I) comprises of three joints (H1, H2 and H3) having different concrete compressive strength and constant axial load on the column. The second group (Group II) comprises of four specimens (H4, H5, H6 and H7) having varying reinforcement in the joint and constant axial load on the column. The third group (Group III) comprises one specimen (H8) with no axial load on the column.

Keywords: Beam-column joint; High strength concrete HSC; Hysteresis loop; Cyclic displacement, Different configuration of beam RFT in joint.

2. Introduction

Reinforced high-strength concrete structures built in zones of low-to-medium seismicity still do not take seismic effect into consideration. In the seismic resisting design one of the most critical areas is the beam-column joint region. Under seismic lateral loading during earthquake, large shearing forces occur in the joint region and joint shear forces may cause joint diagonal tension or compression failure. A beam-column joint becomes structurally less efficient when subject to large lateral loads, such as strong wind, earthquake. The use of HSC has no obvious researches that study its behavior in beam-column joints under lateral loading. Joints design of high rise building is critical issue due to the brittle behavior of HSC compared to normal concrete.

The aim of this paper is to study the behavior of HSC exterior beam-column joints under seismic action and determine the concrete contribution in the shear resistance of HSC joints for different HSC grades. Also, to determine the required reinforcement ratio of suitable detailing to obtain ductile joint behavior. The last objective is to study the effect of column axial load level on joint ductility.

3. Research Significance

The main objective of this research is to evaluate the behavior of high strength concrete beam – column joints, and investigate and the effect of the major test variables:
-The concrete compressive strength.
-Volumetric ratio and spacing of joint transverse reinforcement.
-The axial load level of the column.
-Different configuration of beam longitudinal RFT anchor in joint core.

4. Experimental Program

4.1 Test Specimens

The test program included eight beam-column specimens divided into three groups. The column height from the mid-height of one story to the mid-height of the next one. Table (1) and Fig. (1) shows the detailing in Joint region and the test program and the cross sections in the beam and the column.

Table (1): The Joint Details

Specimen	Applied Axial Load Level	Theoretical Concrete Compressive Strength Fcu MPa (cube)	Joints Hoops			
			Bar Size mm	Spacing mm	Fys N/mm²	Volumetric Ratio of Hoops in Joint core (ρ)
H1	0.12 fc Ag	90	-	-	-	-
H2	0.12 fc Ag	90	-	-	-	-
H3	0.12 fc Ag	60	-	-	-	-
H4	0.12 fc Ag	90	8	50	240	0.012 (Y8@50mm)
H5	0.12 fc Ag	90	8	80	240	0.0075 (Y8@80mm)
H6	0.12 fc Ag	90	10	135	360	0.007 (Y10@135mm)
H7	0.12 fc Ag	90	8	135	240	0.0044 (Y8@135mm)
H8	No axial	90	8	80	240	0.0075 (Y8@80mm)

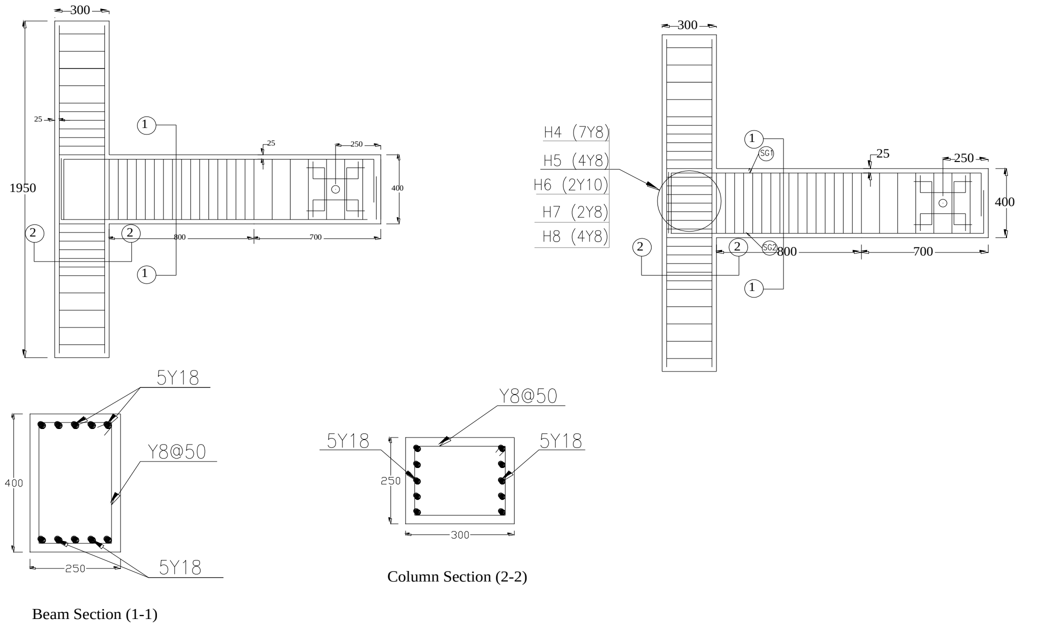


Fig. (1) Details of a Specimen without and with Hoops in Joint Area (Dims. in mm).

4.2 Material Properties

Two different mixes proportions were used in this research. These mixes were designed for desired 28 days compressive strength of 600 kg/cm², and 900 kg/cm². The cement used was Ordinary Portland Cement. The fine aggregate was clean sand, and the coarse aggregate was dolomite with maximum nominal grade size of 10 mm and minimum nominal size 4.75 mm. All the coarse aggregate were sifted in a mechanical sifter to pick the exact nominal size. Potable water was used in concrete mix. Table (3-1) shows the components weight in 1.0 m³ of concrete. Silica fume is a byproduct resulting from the reduction of high purity quartz with coal in electric furnaces in the manufacture of ferrosilicon alloys in Upper Egypt. The extremely small particle size of silica helps to accelerate the chemical reaction of water and cement and has the effect of enhancing the pore structure of concrete. As a result of silica fume additions and relatively higher water absorption of crushed dolomite, there was an increase in the water demand. To produce a concrete of plastic fluid consistency at low water-cement ratio, high range water-reduction admixture (HRWR, or Super plasticizers) locally produced was used. And its main function is to enhance the concrete workability. High strength steel-deformed type of 10, and 18 mm diameter and mild steel-smooth type 8 mm diameter were used in the specimen's reinforcement. Tension tests were performed on the steel using 500-KN universal testing machine. The yield strength, ultimate strength, the elongation percentage were determined from these tests. Also, the area and unit weight were determined.

Table (2): Design of The Concrete Mix (per m^3)

Material in 1m^3	Theoretical Compressive Strength (Kg/cm²) 900	600
Dolomite (10 mm)	1250 Kg	1160 Kg
Fine Aggregate	500 Kg	580 Kg
Cement	495.5 Kg	450 Kg
Silica Fume	55 Kg	-----
Super-Plasticizer*	2 %	1 %
Water	165 liter	180 liter

*Super Plasticizer PVF % of (cement + silica fume)

Table (3): Properties of Steel bars

Nominal diameter (mm)	Nominal Grade	Yield strength (N/mm2)	Ultimate strength (N/mm2)
8	24/35	275.1	450.5
10	40/60	447.7	689.0
18	40/60	440.0	662.0

4.3 Test Setup and Instrumentation:

The test set-up is shown schematically in Fig. (2). The column axial loading system consisted of a hydraulic jack, 1000 KN capacity, connected to a manual pump and a system of plates and rollers that allowed for rotations at the top and bottom ends of the columns.

The beam cyclic loading system consisted of 1000/400 KN reversible hydraulic jack hinged base fixed to the stiff beam supported to the frame main girder. The jack was connected to an electrical pump provided with an automatic valve to control the level and direction of the applied cyclic displacement Fig (3) showed the cyclic load history used in experimental program each cycle repeated twice.

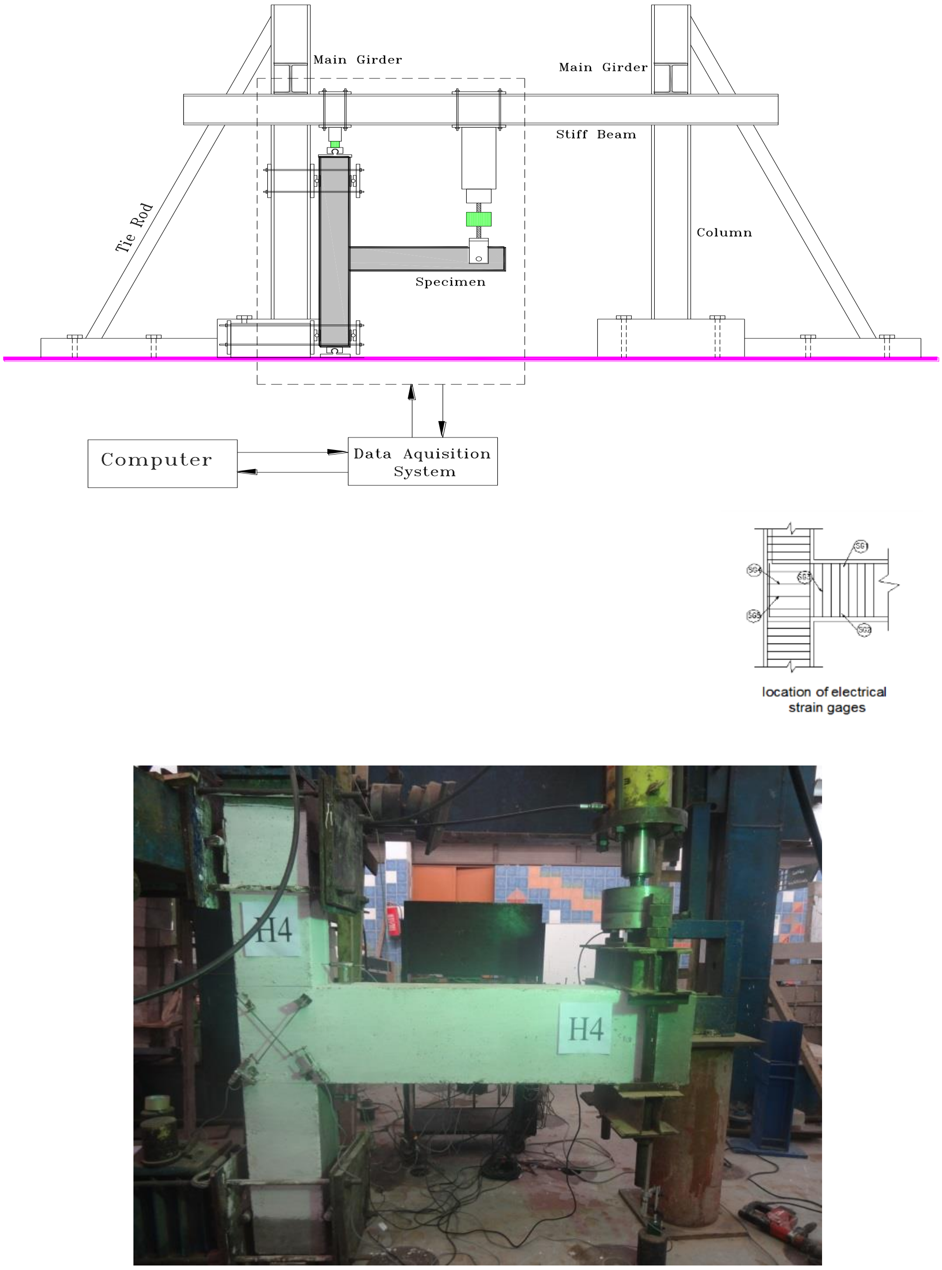


Fig. (2) Test Set-Up

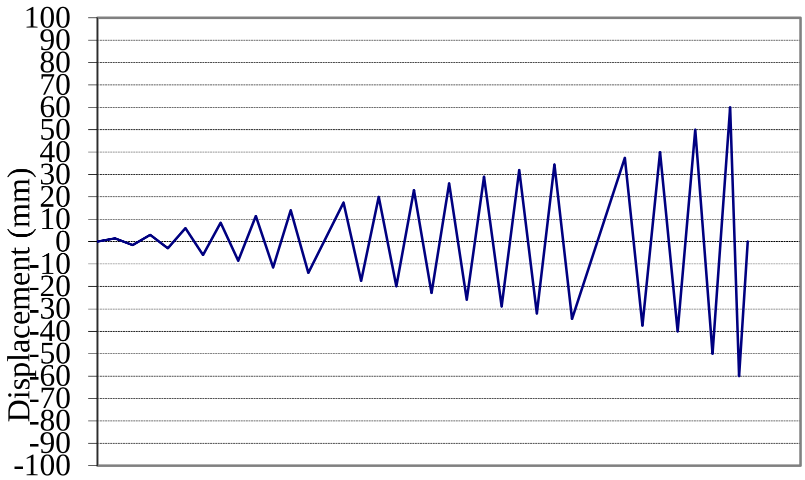
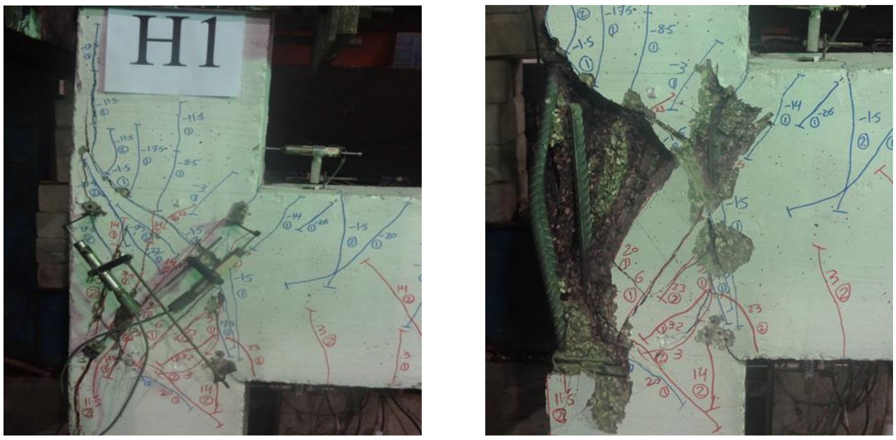


Fig. (3) Cyclic Load History Used in Expermintal Program

5. Experimental Results and Discussion

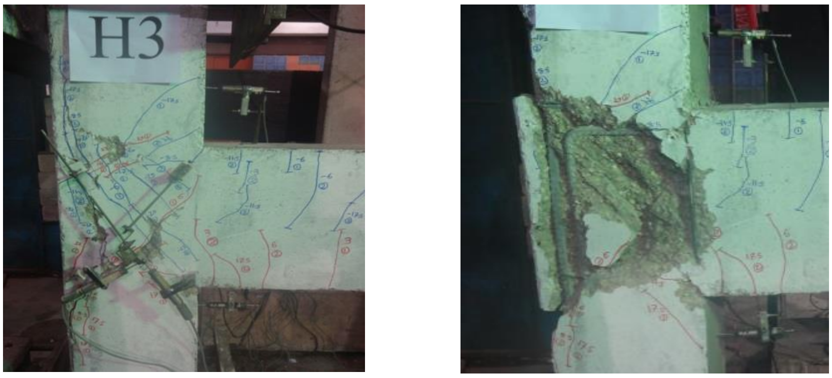
5.1 Cracking Behavior and Mode of Failure

(a) Fine flexural cracks at low displacement, increased at high level of displacements.
(b) After cycle 21th (Δ = 29 mm) no more cracks formed, but got wider.
(c) Diagonal cracks were formed in all joints which increased with loading.
(d) The governor mode of failure was diagonal shear failure inside joint core in all specimens.
(e) At failure, spall of concrete cover in joint core occurred. Hoops opened and column reinforcement started to buckle, as shown in Pics 1 to 8.



Pic. (1) Crack pattern of specimen H1

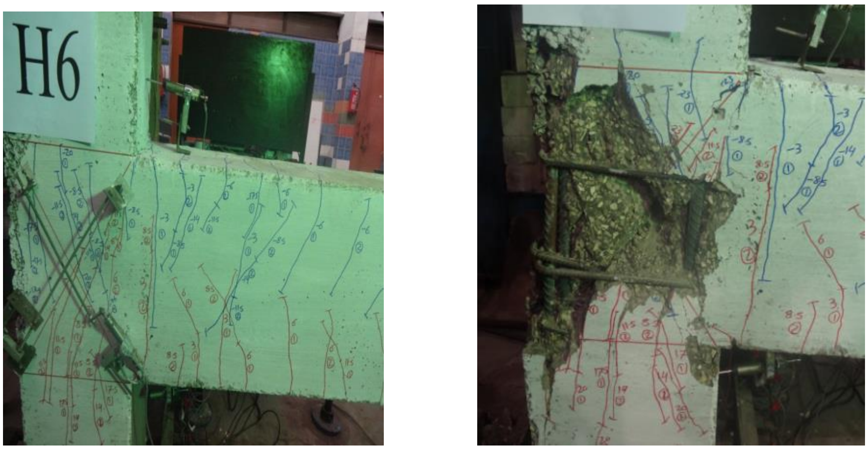
Pic. (2) Crack pattern of specimen H2



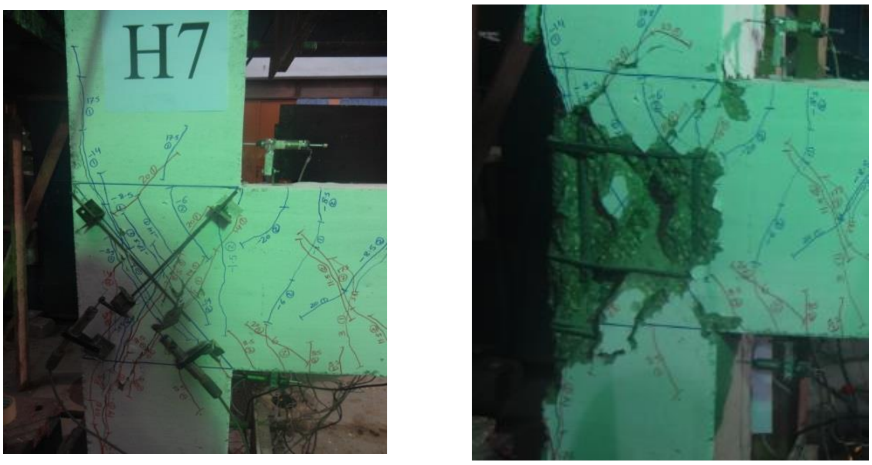
Pic. (3) Crack pattern of specimen H3

Pic. (4) Crack pattern of specimen H4

Pic. (5) Crack pattern of specimen H5



Pic. (6) Crack pattern of specimen H6



Pic. (7) Crack pattern of specimen H7

Pic. (8) Crack pattern of specimen H8

5.2 Load-Displacement Hysteresis Loops

The measured loads were plotted against the associated applied beam tip displacement at different cycles Fig.(4) to Fig.(7) present the experimental load-displacement cyclic loops for specimens H1 to H8; respectively.

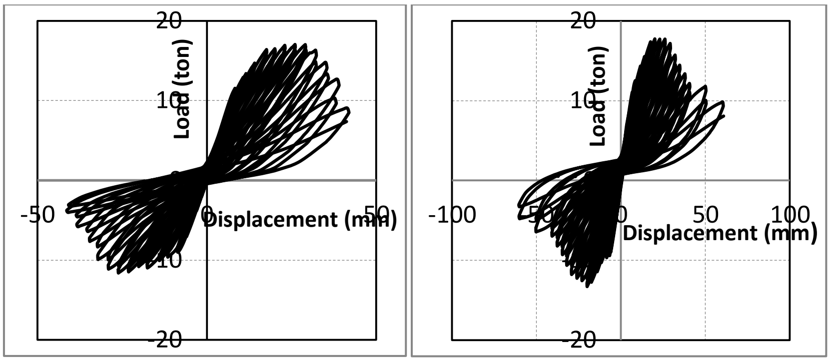


Fig. (4) Load-Displacement Hysteresis Loop of Specimen H1 and H2

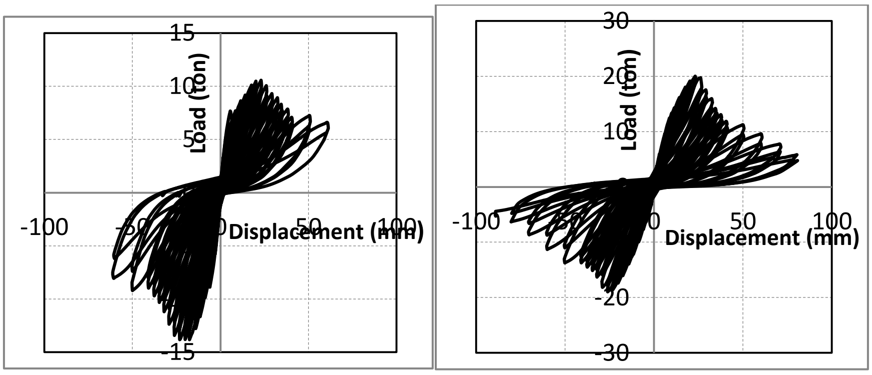


Fig. (5) Load-Displacement Hysteresis Loop of Specimen H3 and H4

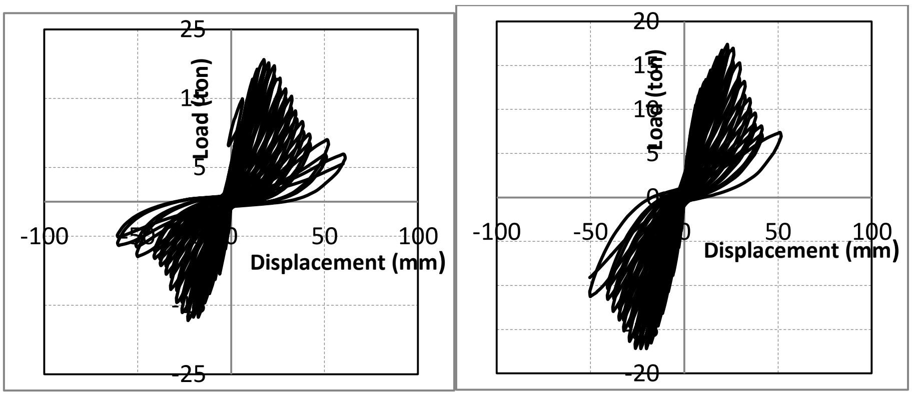
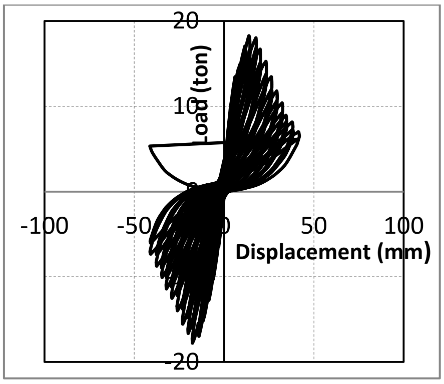


Fig. (6) Load-Displacement Hysteresis Loop of Specimen H5 and H6



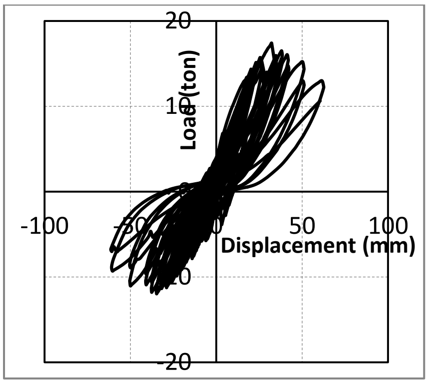


Fig. (7) Load-Displacement Hysteresis Loop of Specimen H7 and H8

6. Analysis of test variables

This section presents method to evaluate ductility, stiffness degradation rate, and energy dissipation to evaluate the performance of beam- column joints under seismic action.

6.1 Displacement Ductility:

$$\mu_{\Delta} = \frac{\Delta f}{\Delta y}$$

Where Δy is the yield displacement and Δf is the displacement at 75% of the ultimate load on the descending branch of load-displacement envelope.

6.2 Strength Decay Rate:

To examine the ability of beam-column to maintain its carrying capacity in the post-elastic range. The strength decay was defined as the raio of the difference between failure and ultimate load to the difference between failure and ultimate displacement.

$$\mathrm{SDR} = \frac{(Pu - Pf)}{(\Delta f - \Delta u)}$$

Where Δu is the displacement at ultimate level, Δf is the maximum displacement at failure and P_u and P_f are the associated loads, respectively.

6.3 Stiffness Degradation Rate:

The decay of the structural resistance to the seismic load can be evaluated based on the loss of the stiffness through loading cycles.

$$\mathrm{KDR} = \frac{(Ko - Ku)}{Ko}$$

Where Ko and Ku are the flexural stiffness of the specimens at initial and at ultimate level, respectively. The stiffness of specimen at each cycle can be calculated as the ratio of the peak load to associated displacement, p/Δ.

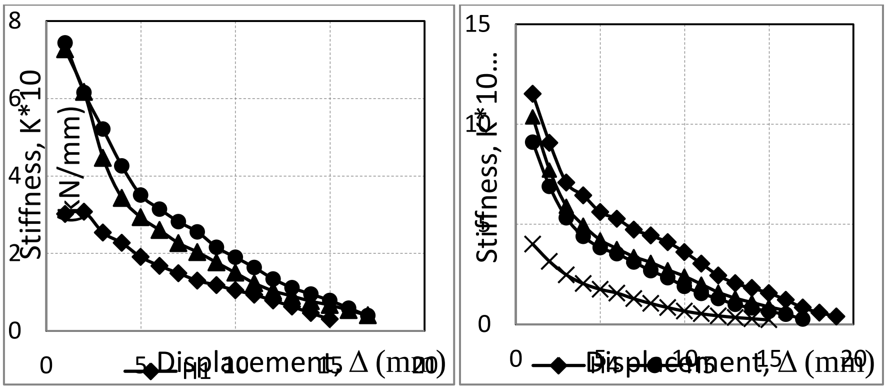


Fig. (8) Stiffness Degradation of GroupI and GroupII

6.4 Energy Dissipation

The ability of structure to dissipate energy due to inelastic deformation is one of the significant factors for a structure to resist seismic action. The more energy dissipated per cycle without excessive deterioration, the better the behavior of the structure.

$$I_{EN} = \frac{1}{Py\,\Delta y}\sum_{i=1}^{n} Ei\left(\frac{Ki}{Ky}\right)\left(\frac{\Delta i}{\Delta y}\right)$$

Where Ei is the energy dissipated during the ith cycle, Δy is the yield displacement of the specimen, Pu is the ultimate load, Ky is the stiffness corresponding to the yield displacement and Δi is the peak displacement of ith cycle and Ki is the corresponding stiffness. The energy index is accumulated until cycle number "n" where the loop peak dropped to 75% of its ultimate value. For groupI: specimen H3 had the biggest energy index equal to 555.4, while specimen H1 had the smallest energy index equal to 126.4. For groupII: specimen H4 had the biggest energy index equal to 717.98, while specimen H6 had the smallest value equal to 213.9. GroupIII: H8 had an energy index equal to 354.9.

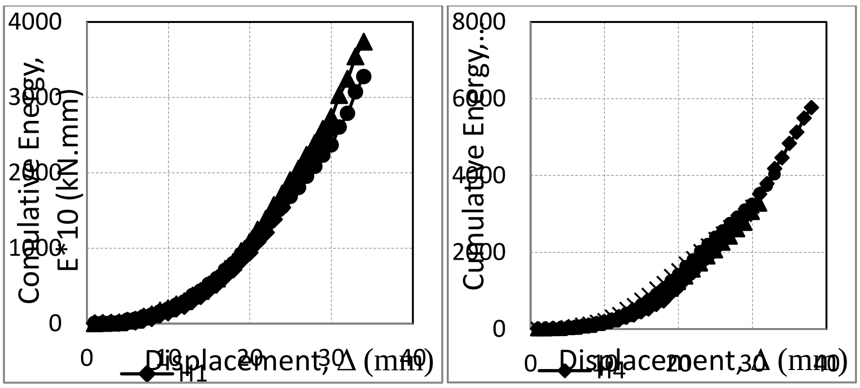


Fig. (9) Energy Dissipated by GroupI and GroupII

7. Effect of Variables

7.1 Effect of Concrete Compressive Strength:

GroupI: H1 and H2 had a compressive strength equal to 900 kg/cm², and H3 had a concrete compressive strength of 600 kg/cm². Fig. (10) showed the effect of using different concrete compressive strength.

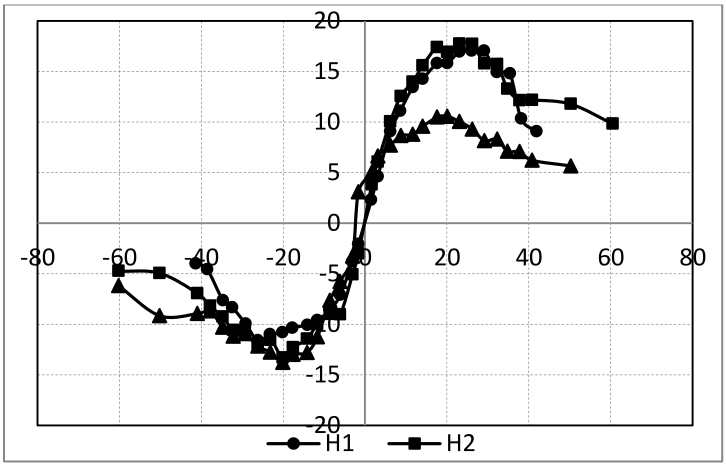


Fig. (10) The Effect of Different Concrete Compressive Strength

7.2 Effect of Transverse Reinforcement in Joint Core:

Fig. (11) presents the envelope of the load displacement for specimens of GroupII. H4 with H5 and H7 which had different spacing and transverse volumetric ratio equal to 5 cm, 8 cm, and 13.5 cm and 0.012, 0.0075, and 0.0044 respectively. The governed modes of failure for these specimens were pure shear failure. Fig. (12) presented the envelope of the load displacement for specimens H5 and H6 which had almost same transverse volumetric reinforcement ratio equal to 0.0075 and 0.00698 but different reinforcement strength grade.

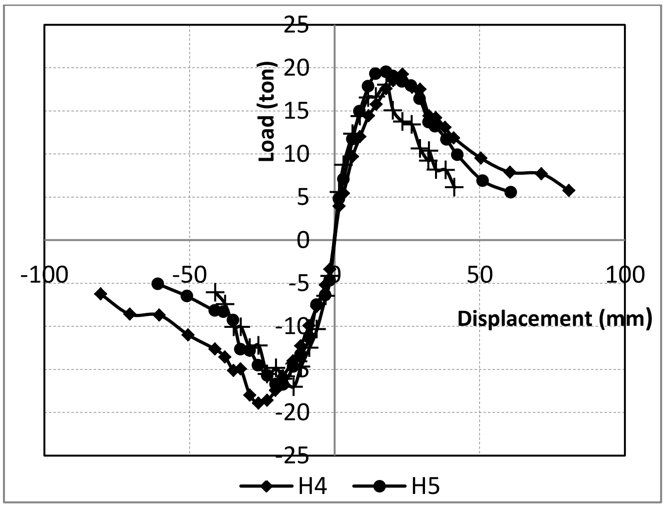


Fig. (11) The Effect of Different transverse Volumetric Ratio in Joint Area

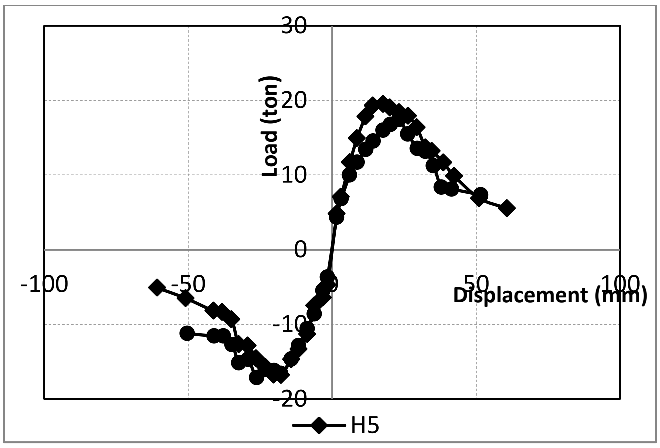


Fig. (12) The Effect of Different Steel Grade with the same transverse Volumetric Ratio in Joint core

8. Conclusion

From the presented study the following conclusion are derived:

- In all specimens the critical section occurred in the joint core. This result agreed with the purpose of the study and the way the specimens were designed.
- Joint shear mode of failure governed the behavior of all specimens.
- The applied displacement pattern in the quasi-static testing was rational to the beam capacity in both upward and downward loading directions. As a result, in all specimens the ultimate load was reached in both direction of loading in the same loading cycle.
- The existence of hoops helped to decrease the difference between the joint ultimate shear strength in the upward and downward directions.

➢ **Ultimate Shear Strength:**

Concrete Compressive Strength: Specimens with strength equal to 900 kg/cm² carried higher load than specimen with strength 600 kg/cm² by 39.6% in upward direction.

Volumetric Ratio and Spacing of Joint Transverse Reinforcement:

- Using hoops volumetric ratio ρv = 0.0044 improved joint ultimate shear strength by 25% in downward direction and 3.33% in upward direction compared to joints without hoops in joint core.
- Increasing ρv to 0.012 improved the joint ultimate shear strength by 5% in downward direction and by 10% in upward direction compared to ρv = 0.0044.
- Using different steel grad with same ρv in H5 and H6 increased the ultimate shear strength in H5 in upward direction by 15.5%.

Axial Load Level: the absence of axial load made the maximum ultimate strength decreased by 16.5% to 31% comparing with H5 which had the same hoops in joint core but under axial load.

Different Configuration of Beam Longitudinal RFT Anchor in Joint Core: - In the load direction, where the beam longitudinal tension reinforcement was bent away from joint core a reduction in ultimate joint shear strength for the same concrete compressive strength of about (23.6% to 32%) comparing to the configuration with tension reinforcement bent inside the joint core.

- The existence of hoops decreased the difference between ultimate shear strength by 9% in downward direction and 15.5% in upward direction for joints with unsymmetrical configuration of anchor of beam tension reinforcement in joint core.

- The direction where tension longitudinal reinforcement bent away from joint core the ultimate shear strength was reduced about 31 % although the joint had hoops in joint core in specimen with no axial load level on column.

Ductility: The specimens with no hoops in joint core the governor in ductility was their concrete strength. H3, (with strength 600 kg/cm²) was more ductile than specimens H1 and H2. For the other specimens, the existing of hoops in joint core didn't make an obvious effect in displacement ductility. For normalized ductility (IEN), groupI: H3 dissipated energy more than other specimens by 77.24%.
On the other hand, Different Hoops Volumetric Ratio: The hoops helped the concrete strut mechanism by confining the joint core and during cycling load. Normalized ductility (IEN), for groupII: The dissipated energy index of specimen H4 is more than the value of the other specimens by 70.2%.While using different steel grade but the same volumetric transverse ratio in H5 and H6 made H5 (four hoops eight millimeters in diameter in joint core) more ductile and the dissipated energy index were more than H6 (two hoops ten millimeters in diameter in joint core) by 39.6%.

9. References

1- Park, R. (1988). Ductility evaluation from laboratory and analytical testing. Proceedings of 9th World Conference on Earthquake Engineering - 9WCEE, Tokyo, Japan, 8:605-616.
2- Paulay T. and Park R. (1984). Joints in Reinforced Concrete Frames designed for Earthquake Resistance. Dept. of Civil Engineering. University of Conterbury. Christchurch. New Zealand.
3- FEMA-451 (2006). Recommended provisions: Design examples. Federal Emergency Management Agency, FEMA, Washington, USA.
4- Salse, E., Fintel, M. (1973). Strength, stiffness and ductility properties of slender shear walls. Proceedings of 5th World Conference on Earthquake Engineering - 9WCEE, Rome, Italy, 918-928.

5- Ehsani M. R., and Wight J. K., "Confinement Steel Requirements for Connections in Ductile Frames" Journal of Structural Engineering, ASCE, Vol.116, No. 3, March, 1990.

6- M. R. Ehsani and J. K. Wight "Effect of Transverse Beams and on Behaviour of Reinforced Concrete Beam-to-Column Connection", ACI Structural Journal, Vol.82, No.2, March-April 1985, pp 188-196.
7- Kaku T., and Asakusa H., "Ductility Estimation of Exterior Beam-Column Subassemblages in Reinforced Concrete Frames", Design of Beam Column Joints for Seismic Resistance, SP 123, American Concrete Institute, Detroit, 1991, pp. 167-185.
8- Rajesh P Dhakal "Structural Design for Earthquake Resistance: Past, Present and Future.
9- Park R., and Paulay, T., —*Reinforced Concrete Structures*‖, John Wiley & Sons, First Edition, 1975, pp. 769.
10- Yehya, M.A, "Seismic Behaviour of Strengthened Reinforced Concrete Columns" PHD Thesis submitted to Cairo University, 1999.
11- Bahaa, T.M, "Seismic Behaviour of Reinforced High-Strength Concrete Beam-Column Joint with and without Steel Fibers" PHD Thesis submitted to Cairo University, 2002.