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Shear Strengthening of Reinforced Self-Compacted Concrete Hammer Head Beams Using Warped CFRP Strips: Experimental and Theoretical Study

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ABSTRACT

Despite the many investigations on shear behavior of reinforced concrete beams, shear failure mechanism of hammer head beams is still not well understood. In the present paper, tests were carried out on six hammer head beams (double cantilever) under the effect of two-point loading. Five beam specimens were hammer head (non-prismatic shape) beams, while the last one has a rectangular prismatic shape. The adopted variables were: the shape of the tested beams, amount of shear reinforcement and strengthening by CFRP strips. Three-dimensional finite element analyses by using ANSYS software were performed to verify the experimental results for all beams. Parametric study was performed based on two parameters, compressive strength of concrete ($f'c$) and slope angle ($\alpha°$). Therefore, nine additional beam specimens were modelled and analyzed. Test results showed that hammer head beams without web reinforcement have a superior shear capacity by about (12%) as compared with the prismatic hammer head beam and that strengthening by CFRP for hammer head beams enhances the shear capacity by about (30%). Analytical results showed that increasing concrete compressive strength from (25MPa) to (60MPa) gives an increase in ultimate load capacity by about (38%) for non-prismatic beams and by about (63%) for prismatic beam in case of absence of web reinforcement. Also, it was found that in case of no web reinforcement, the increase of slope angle from (0°) to (5°) and (10°) improves shear capacity.

KEYWORDS: Finite element, ANSYS, Shear, Self-compacted concrete, Hammer head beam, ACI-318.

INTRODUCTION

Since the first half of the 20th century, new forms of beams had arisen, one of which is called hunched (or hammer head) beam. This kind of beam is used usually for mid-rise framed buildings and in simply supported or continuous bridges as lateral hammer head beams. Actually, the design of reinforced concrete hunched beams (RCHBs) has been left to judgment and experience of structural engineers in professional practice, because the available codes and specifications such as (ACI-318M-2011) (American Concrete Institute) or (BS-5400 1988) (British Standard Institute) do not cover these member types. Structural engineers and architects are often tending to use such non-prismatic beams because of the following advantages compared to prismatic beams: (a)-Hunched beams substantially increase the lateral stiffness of buildings, which allows the designer to control code drift limits; (b) Such beams lead to a more efficient use of concrete and steel reinforcement; (c) such beams reduce the

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weight of structure for a given lateral stiffness; (d) The utilization of hunched beams facilitates the placement of air conditioning, building's electrical and sewage equipment,… etc. (Tena – Colunga, 1994; Cuevas et al., 2008).

Previous review of experimental and numerical studies of reinforced concrete beams shows that the behaviors of hunched beams attracted the interest of few researches. The shear strength of RCHBs with shear reinforcement was reported by Debaiky et al. (1982), El-Niema (1988) and Stefanou (1983). Tests on RCHBs without shear reinforcement were reported by MacLeod et al. (1994). Experimental and theoretical investigations on shear strength evaluation of reinforced self-compacted concrete hammer head beams are presented in the current paper.

SIGNIFICANCE OF THE PRESENT STUDY

There are few researchers who studied hammer head reinforced concrete elements and their shear failure mechanism is still not well understood. The present study deals, experimentally and theoretically, with the structural behavior of reinforced concrete hammer head beams, as well as the strengthening technique by using CFRP strips to enhance the shear capacity.

EXPERIMENTAL STUDY

Tests were carried out on six hammer head beams under the effect of two-point loading at the ends. Five beam specimens were hammer head beams (non-prismatic shape), while the last one was of rectangular prismatic shape. The dimensions of the hammer head beams were kept constant for all tested beams. The variables were: shape of the tested beams, amount of shear reinforcement (stirrups) and strengthening by CFRP strips. For all tested beams, the span, concrete strength and tension (flexural) reinforced bars at the top were kept constant. It can be noted that the tested beams have been designed to ensure shear failure. The hammer head specimens had an overall length of (2000mm), a width of (400mm) and a variable depth of (300mm) in the middle, reduced linearly to be (150mm) at the tips. The prismatic beam had an overall length of (2000mm), a width of (400mm) and a depth of (300mm). The amount of the top flexural reinforcement for all the tested beams was (5∅ 20mm) (ρ_{max} = 0.0218), where ρ_{max} is the maximum flexural reinforcement ratio according to (ACI 318M-2011) (used to ensure the shear failure to take place for all tested specimens). For the lower cord of the tested beams (2∅10mm) , the same shape of compression cord was used. The web reinforcement (share reinforcement) consists of (∅6mm) with different spacings, see Plate (1). The beam specimens were tested under two symmetric loadings with an overall clear span of (1800mm). To prevent load concentration (any local crushing in concrete), bearing plates under each load and above the support have been placed. It may be noted that each beam was designated in a way to refer to the beam type (Hammer Head Beam=TB or Prismatic Beam=PB), quantity of web reinforcement (stirrups) (Without=0S, Half-minimum web reinforcement =0.5S, Minimum web reinforcement=1S) and presence or absence of CFRP (Without CFRP=WC, With CFRP inclined with an angle of 45^o= C45^o). Therefore, for example, the beam (TB-0S-C45°) is a hammer head beam specimen made without web reinforcement and strengthened by CFRP inclined with an angle of 45^o. Details of the tested beams are shown in Table (1) and descriptions of beam specimens (TB-0S-WC) and (TB-0.5S-C45°) are shown in Figs.(1) and (2).

Plate (1): (a) Putting steel reinforcement cage in mold (b) Beam specimen casting

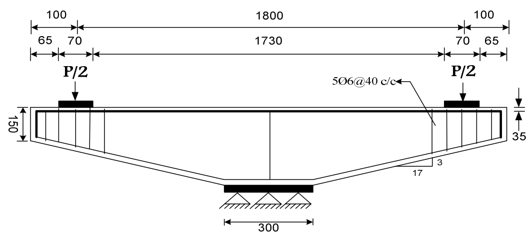

Figure (1): Details of hammer head beam (TB-0S-WC)

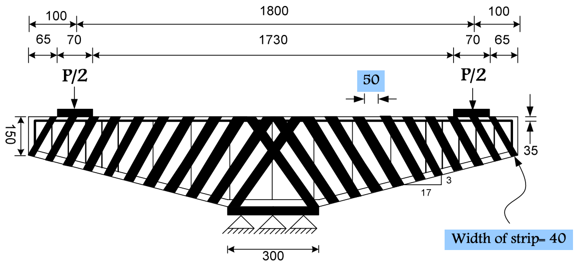

Figure (2): Details of hammer head beam (TB-0.5S-C45°)

Properties and description of the used materials are reported and presented in Table (2) and concrete mix proportions are reported and presented in Table (3).

Table 1. Beam specimen details

Beam Designation	Shape of Beam	Shear Reinforcement (Stirrups)	Strengthening By CFRP Strips
TB-0S-WC	Hammer head	Without web reinforcement	Without
TB-0.5S-WC	Hammer head	Half-minimum web reinforcement	Without
TB-1S-WC	Hammer head	Minimum web reinforcement	Without
TB-0S-C45 º	Hammer head	Without web reinforcement	With
TB-0.5S-C45º	Hammer head	Half-minimum web reinforcement	With
PB-0S-WC	Prismatic	Without web reinforcement	Without

Table 2. Properties of construction materials

Material	Description
Cement	Ordinary Portland Cement (Type I)
Sand	Natural sand from Al-Ukhaider region with maximum size of (4.75mm)
Gravel	Crushed gravel of maximum size (19 mm)
L. S. P.	Fine limestone powder (locally named as Al-Gubra) of Jordanian origin
Super-plasticizer	Glenium 51 manufactured by BASF Construction Chemicals, Jordan
Reinforcing Bars	(ϕ20mm) deformed steel bar, having (500 MPa) yield strength (f_y) (ϕ10mm) deformed steel bar, having (420 MPa) yield strength (f_y) (ϕ6mm) deformed steel bar, having (363 MPa) yield strength (f_y)
Water	Clean tap water

Table 3. Proportions of concrete mix

Material						
Cement (kg/m^3)	**Fine Aggregate (kg/m^3)**	**Course Aggregate (kg/m^3)**	**Limestone Powder* (kg/m^3)**	**Water (kg/m^3)**	**W/C**	**Super-plasticizer** (L/m^3)**
450	797	767	170	170	0.38	10

* Limestone (LSP) (0.37% of cement). ** Super-plasticizer (2.23% of cement)

The compressive strength and tensile strength of concrete are measured based on (ASTM C39-1996), (BS1881-116 1983), (ASTM C496-2011) and (ASTM C78-1975), respectively. All beam specimens have been removed from curing at the age of 28 days (except two strengthened beams which were removed two days before). The beam specimens have been cleaned and painted with white paint before the testing day in order to clarify crack propagation. To satisfy test requirements, the beam specimens have been rotated with an angle of (180°) for more stability before and during the test, as shown in Plate (2). Vertical deflection was measured at the tips of beam specimens by using a dial gauge of (0.01mm/div.) accuracy at every load stage, see Plate (2).

Plate (2): Test procedure for hammer head beams

The load in the test machine was applied by hydraulic pressure on the bottom side and the upper partition only to restrain the tested specimens and stop directly after touch occurs with specimen. The beam specimens have been loaded in increments of (10kN) and the rate of load increment was about (1.5kN/sec). The positions and extents of the first and the other consequent cracks were marked on the surface of the beam. When failure occurred, the beam failed abruptly at the same time when the load indicator stopped recording or returned back and the deflection increased very fast. The failure load has been recorded and the hydraulic load removed.

THEORETICAL STUDY

To study more thoroughly the structural behaviour of the tested beams, three-dimensional finite element analyses by using ANSYS (version-15) software were performed. The theoretical study includes, in additional to verifications of all experimental beams, modelling and analyzing of nine additional beam specimens. A nonlinear, eight-node brick element, (SOLID-65), with three translation DOFs at each node was used to model the SCC. For FEM modelling of the steel reinforcement, a two-node, discrete axial element, (LINK-180), with three translation DOFs at each node was used. (SHELL-41) element with three translation DOFs and three rotation DOFs per node was used to represent CFRP strips. In ANSYS software, the real constants, such as cross-sectional area and thickness, are needed to represent the geometrical properties of the used elements. The material properties are needed to represent behaviour and characteristics of the constitutive materials which depend on mechanical properties, such as: yield stress, modulus of elasticity, Poisson`s ratio and stress- strain relationship. The use of a rectangular mesh is recommended to secure good results from the concrete element (Solid-65); therefore, a rectangular meshing was applied to model all beam specimens.

The parametric study presented here consists of modeling and analyzing of nine additional beam specimens using ANSYS software. The parameters considered in this study are concrete compressive strength ($f'c$) and slope angle (α), Table (4).

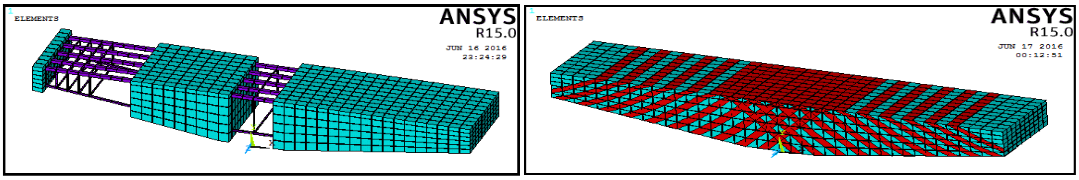

Figure (3): Modeling of reinforcing steel bars and CFRP for hammer head beam

Table 4. Parametric study parameters

Beam Designation	($f'c$) (MPa)	(f_t) (MPa)	(Ec)** (MPa)	(α) (Degree)	Variable Considered
TB-0S-WC*	25	3.1	23511	10°	($f'c$) (MPa)
HTB-0S-WC	60	4.8	36406	10°	
TB-0.5S-WC*	25	3.1	23511	10°	
HTB-0.5S-WC	60	4.8	36406	10°	
TB-1S-WC*	25	3.1	23511	10°	
HTB-1S-WC	60	4.8	36406	10°	
PB-0S-WC*	25	3.1	23511	0°	
HPB-0S-WC	60	4.8	36406	0°	
TB-0S-WC*	25	3.1	23511	10°	(α) Slope Angle (Degree)
TB5°-0S-WC	25	3.1	23511	5°	
PB-0S-WC*	25	3.1	23511	0°	
TB-0.5S-WC*	25	3.1	23511	10°	
TB5°-0.5S-WC	25	3.1	23511	5°	
PB-0.5S-WC	25	3.1	23511	0°	
TB-1S-WC*	25	3.1	23511	10°	
TB5°-1S-WC	25	3.1	23511	5°	
PB-1S-WC	25	3.1	23511	0°	

*Experimental specimen, molded by ANSYS for comparison study. **ACI-318-M11.

RESULTS AND DISCUSSION

Table (5) shows the comparison between the ultimate loads of the experimental (tested) beams, (Pu)E, and the final loads from the finite element models, (Pu)N. The final loads for the finite element models are the last applied load steps before the solution starts to diverge due to numerous cracks and large deflections. It can be observed that there is a simulation between the finite element analysis and the experimental results by about (95%) for ultimate load capacity (Pu) and about (86%) for ultimate deflection (Δ_f) and these ratios are considered reasonable and accepted. Crack patterns obtained from the finite element analysis and the failure modes of the experimental beams agree well, as shown in Fig. (4).The appearance of the cracks reflects the failure mode for the beams. The finite element model accurately predicts that the beams fail in shear. The cracks were concentrated in the shear span region, which vanishes diagonally towards the beam supports.

Figure (4): Crack patterns of beam specimen (TB-0S-WC)

The load *versus* deflection plots obtained from the numerical study together with the experimental plots are presented and compared in Fig. (5). In general, it can be noted from the load-deflection plots that the finite element analyses agree well with the experimental results throughout the entire range of behaviour.

Table 5. Numerical and experimental results for all specimens

Beam Designation	Experimental Results		Numerical Results		Load Factor (Lf) PuN/ PuE	Deflection Factor (Df) Δf N/ Δf E
	P_{uE}(kN)	Δ_{fE} (mm)	P_{uN}(kN)	Δ_{fN}(mm)		
TB-0S-WC	322.5	6	312.25	4.85	0.97	0.8
TB-0.5S-WC	386	7.15	381.75	6.1	0.99	0.87
TB-1S-WC	430	8	428.25	7.12	0.99	0.89
TB-0S-C45 º	437	7.35	427	6.85	0.98	0.93
TB-0.5S-C45º	485	8.65	443.5	7.1	0.91	0.82
PB-0S-WC	287.5	4.1	251.84	3.49	0.875	0.85
AVARAGE					0.95	0.86

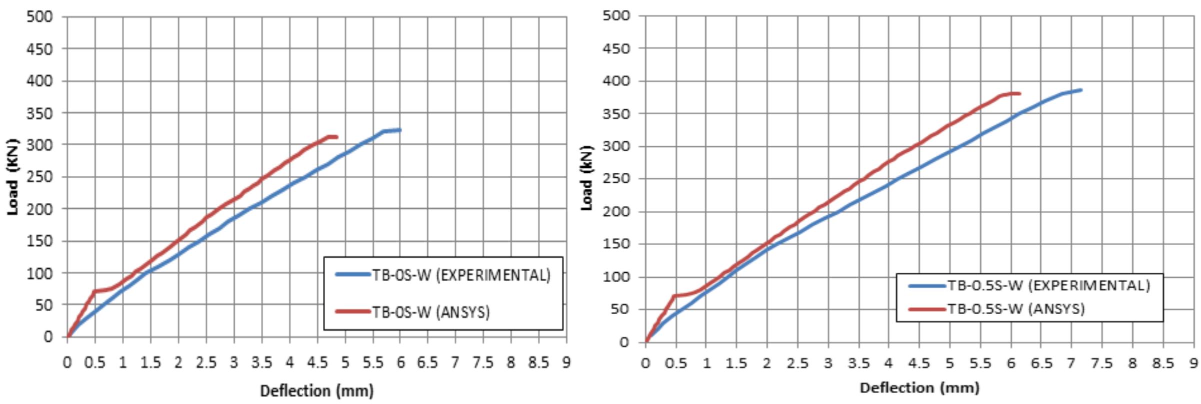

Figure (5): Numerical and experimental load-deflection relationships

Two grades of concrete compressive strength have been used. The numerical results of ultimate load capacity (Pu) and the corresponding tip deflection (Δf) are shown in Table (6). Increasing (*fc'*) from (25MPa) to (60MPa) leads to an increase in the ultimate capacity (Pu) by about (39%), (54%), (54%) and (63.3%) for the beams (HTB-0S-WC), (HTB-0.5S-WC), (HTB-1S-WC) and (HPB-0S-WC), respectively. Numerical results of ultimate load (Pu) and the corresponding tip deflection (Δf) are shown in Table (7). When (α) changed from (10°) to (5°) then to (0°), the ultimate load (Pu) decreased by (7.6%) and (10.8%), respectively.

Table 6. Ultimate load and displacement for the numerically analyzed specimens

Beam Designation	Actual Numerical Results		Corrected Results (Expected Experimental Results)			
	Pu (kN)	Δf (mm)	Pu/Lf (kN)	Change in (Pu) %	Δf /Df (kN)	Change in (Δf) %
TB-0S-WC*	312.25	4.85	322.5	38.6	6	16.6
HTB-0S-WC	434	5.6	447		7	
TB-0.5S-WC*	381.75	6.1	386	53.7	7.15	118
HTB-0.5S-WC	588.52	13.58	594		15.6	
TB-1S-WC*	428.25	7.12	430	53.7	8	123
HTB-1S-WC	654.75	15.94	661		17.9	
PB-0S-WC*	251.84	3.49	287.5	63.3	4.1	22
HPB-0S-WC	411.25	4.32	470		5	

Lf= Load Factor. Df=Deflection factor, see Table (5).

Table 7. Effect of hammer head slope angle on the ultimate capacity and corresponding deflection

Beam Designation	Actual Numerical Results		Corrected Results (Expected Experimental Results)			
	Pu (kN)	Δf (mm)	Pu/Lf (kN)	Change in (Pu) %	Δf /Df (kN)	Change in (Δf) %
TB-0S-WC*	312.25	4.85	322.5	-	6	-
TB5°-0S-WC	275.1	3.65	298	-7.6	4.42	-26.3
PB-0S-WC*	251.84	3.49	287.5	(-10.8)	4.1	(-31.6)
TB-0.5S-WC*	382	6.1	386	-	7.15	-
TB5°-0.5S-WC	352.62	4.92	382	-1	6	-16
PB-0.5S-WC	333.24	4.64	381	-1.2	5.4	-24.4
TB-1S-WC*	428.25	7.12	430	-	8	-
TB5°-1S-WC	413	5.95	448	+4.1	7.2	-10
PB-1S-WC*	413	5.87	472	+9.7	6.9	-13.7

Lf= Load Factor. Df=Deflection factor, see Table (5).

CONCLUSIONS

1. Hammer head beams without web reinforcement have a superior shear capacity by about (12%) and more deformation response by about (46%) as compared with the prismatic hammer head beam. Strengthening of hammer head beams enhances the shear capacity by about (30%) increasing the confidence of member. The increment ratio of load capacity for hammer head beam with half-minimum and minimum web reinforcement for prismatic beam was (20%) and (33%), respectively; this load capacity increment is associated with an increment in deformation response by about (18.3%) and (33%), respectively.
2. In the absence of web reinforcement, increasing of

the ultimate compressive strength of concrete ($f'c$) from (25MPa) to (60MPa) gives an increase in ultimate load capacity of hammer head beams by about (38%) and by (63%) for prismatic beam. In the case of hammer head beams with minimum and half-minimum web reinforcement, increasing the ultimate compressive strength of concrete ($f'c$) from (25) to (60) MPa leads to change the mode of failure from shear failure to flexural failure and increases the ultimate load capacity by about (54%).

3. For modeled beams which have no web reinforcement, as the hammer head slope angle decreased from (10°) to (5°) and (0°) (the total volume of the concrete increased from (-20%) to (-10%) and (0%)), the shear capacity decreased by about (-7.6%) and (-10.8%) and deformation response by about (-26.3%) and (-31.6%). For modeled beams which have half-minimum web reinforcement, the effect of hammer head slope angle approximately disappears on the shear capacity of the member. However, the deformation response decreased by about (-16%) for beams with (5°) slope angle and by about (-24.4)% for beams with (0°) slope angle as compared with beams with (10°) slope angle. In the case of minimum web reinforcement, the effect of hammer head slope angle is inverse on the shear capacity of the member, since as the hammer head slope angle decreased from (10°) to (5°) and (0°), the shear capacity increased by about (+4.1%) to (+9.6%), but the beams with (5°) and (0°) slope angle still have less deformation response by about (-10%) and (-13.7%) as compared with hammer head beams with (10°) slope angle.

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