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Performance of Composite Concrete T-Beams Cast in Steel Channels with Headed Studs of Various Lengths and Dimensional Proportions

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Abstract

The observations and digital interpreted results of four simply supported composite reinforced concrete T-beams with steel channels tested up to failure under four-point loading condition simulating approximately the central 1-m uniformly distributed load, are reported and discussed. Three of those beams were provided with headed studs. The variables were the headed stud shank length relative to the flange width of the steel channel and the breadth of the T-section beam, in addition to the existence or absence of shear connectors. The first beam was destitute of headed studs; while the three other beams were provided with headed studs of moderate length (equal to the steel channel flange width), 30% longer length, and 30% shorter length, beam. The beam with headed studs of moderated lengths has revealed substantial preeminence-of diverse numerical values-in the respects of flexural stiffness, ductility and ultimate resistance, relative-slip constraint, and integrity characteristics for which mechanically-based argumentation is set forth. In spite of the concrete confinement in the zone of the steel channel, drastic drops in levels of the integrity and the ultimate bending resistance have occurred when shear connectors were eliminated.

Key Words :Reinforced Concrete, Composite Integrity, T-beams, Steel Channels, Headed Studs, Uniform Loading, Cracking load, Ultimate Load, Fracture Pattern .

الخلاصة:

تم تقرير ومناقشة المشاهدات والنتائج الرقمية المفسرة لاربعة روافد خرسانية مركبة ذوات مقطع T مزودة بسواقي حديدية ومفحوصة لغاية الفشل تحت حالات تحميل ذوات اربعة احمال نقطية والتي تحاكي تقريبا الاحمال المركزية المتجانسة التوزيع بطول متر واحد .كانت المتغيرات هي طول ساق رابط القص الوتدي ذي الرأس نسبة الى عرض طوق مقطع حديد الساقية المستخدم ، والى عرض الرافدة ذات المقطع T ، إضافة الى وجود او غياب روابط القص . لقد كانت الرافدة الأولى خالية من روابط القص الوتدية ، بينما تم تزويد الروافد الثلاثة الباقية بروابط قص وتدية

بأطوال معتدلة (مساوية الى عرض طوق حديد الساقية ، وبأطوال تزيد بنسبة ٣٠ % ، وبأطوال تقل بنسبة ٣٠ % ، وبواقع حالة واحدة لكل رافدة .اظهرت الرافدة ذات الروابط الوتدية معتدلة الطول تفوقا كبيراً ن وبقيم عددية متنوعة في مجالات الجسائة والمطاوعة والمقاومة القصوى الانثنائية ، تقييد الانزلاق النسبي ، وخصائص الوحدة التمامية ن حيث تم إقرار مناقشة لتلك الظواهر مبنية على أساس ميكانيكي . على الرغم من احتجاز الخرسانة في نطاق حديد الساقية ، فقد حصلت انخفاضات حادة في مستويات مقاومة الانحناء القصوى والوحدة التمامية.

1- Introduction

Reinforced concrete T-beams cast in steel channels represent a typical state of **''Composite Reinforced Concrete "** achieving a unique method of combining steel and concrete that utilizes both the *material* advantagesof *reinforced concrete* and the *constructional* advantages of *composite construction*.
From the material standpoint, the present steel-concrete combination is very close in its action to reinforced concrete-indeed in effect it is *reinforced concrete with external reinforcement*. Then the steel content in the two systems is used much more efficiently, i.e. quite near the soffit, giving a lever arm which is a high proportion of the beam full depth, and the required cross-sectional area of the steel channel is thereby reduced. In accordance, the required number of shear connectors is considerably reduced as it is approximately proportional to the cross-sectional area of the steel section used. In this respect, the situation for the *traditional* composite construction is quite different.
Recalling that the traditional composite construction is cheaper-from the constructional standpoint-than the in situ reinforced concrete, the present steel-concrete combination acquires this standpoint economical property. A steel framework of beams and columns can quickly be erected. Thereby, the concrete floors can be constructed much more easily than with the completely in situ reinforced concrete structure, particularly when precast concrete units or profiled steel sheeting are used in conjection with the steel frame to facilitate the construction of the floors.
Many of the complex behaviors of *"Composite Reinforced Concrete"* under shear and flexure are yet to be identified to employ this *material assembly* advantageously and economically. Hence, further basic research should be encouraged to determine the geometrical features and dimensional proportions which result in the optimum failure of composite reinforced concrete members.

2- Review

Numerous research work has yet been published in the spacious field of *normal* composite construction. Nevertheless, the progress in the understanding and quantitative assessment of the behavior of "*Composite Reinforced Concrete*" members subjected to flexure and shear has been less spectacular.

A literature review reveals that a few number of studies was performed on composite reinforced concrete T-beams .The beginning was in **1972** due to Taylor (cited in Ref.[1] , **pp.8-11**) when he suggested the possibilities of such construction, followed by the first tests carried out in **1972** by **Taylor and Burdon** [2] on three series of nine simply supported reinforced concrete T-beams with steel channels.

Taylor , et al. [3] suggested in **1974** transverse –bolt shear connectors in composite reinforced concrete for which push-off tests were carried out to ascertain their strength .The competitive shear connector was the transverse bar suggested by **Taylor and Cunningham** [4] in **1977**. **Asaad** [5] , in the same year, performed tests on simply supported inverted composite reinforced concrete T-beams simulating the hogging moment regions of continuous beams with the midspan load representing the column support. In **1978**, again **Taylor, et al.**[6] published test results of six beams containing prestressing strands as part of tensile reinforcement . Further tests on six inverted hogging beams were reported by **Taylor and Al –Najmi** [7] in **1980**, followed by a further analysis on the same beams in an attempt to asses the strength of confined concrete in the compression zone [8]. Advantages, drawbacks and precautions for composite reinforced concrete beams were presented by **Taylor** [9], in **1980**. In **1982 Kettoola** [10] tested four inverted T- beams with steel channels , simulating them as parts of continuous beams to investigate their behavior in shear and hogging bending , followed by **Jasim**'s [11] , tests on other similar beams but for sagging bending investigation.

The findings and suggestions of those studies were not substantiated by further studies, where nothing is available in literature except three recent researches .The first is in **2007** by **Abdul Hussien** [12] concerning finite element analysis for concrete T- beams of webs partially casted in steel channels. **Al-Hadithy and Al-Kerbooli** [13] in **2009** performed laboratory tests and finite element analysis on four reinforced concrete beams cast in steel channels and other four reinforced concrete beams without steel channels to examine their flexural stiffnesses , ductilities and ultimate bending capacities in addition to same parametric effects. Finally, **Al-Ta'ai** [14] presented a finite element analysis on composite reinforced concrete T- beams with webs entirely enclosed by large steel channels.

3- Theme and Objectives

It was planned [9] to change the *traditional composite construction* to something very close to reinforced concrete-i.e. Reinforced concrete with external reinforcement-by the so called "*Composite Reinforced Concrete*" consisting of reinforced concrete T-beams cast in steel channels with headed studs (primarily responsible for provision of horizontal shear interaction). However, this would not be realized *unless longitudinal and transverse reinforcements are provided*-as in **Fig. 1**-to prevent any tendency to separate the steel channel off the abutting concrete (in the form of horizontal longitudinal cracking occurring above the shear connectors). This is achieved by producing compressive struts between the *underside* of the stud head and the longitudinal bars which, in turn, convey those forces to the transverse reinforcement (stirrups) as shown.

While the enclosure of the longitudinal reinforcing bars by transverse stirrups is an important fact of normal reinforced concrete, the steel channel-which forms a significant proportion of the longitudinal steel-is not enclosed by any transverse link. Anywise, the headed studs *will, definitely, tend to produce the same effect.*

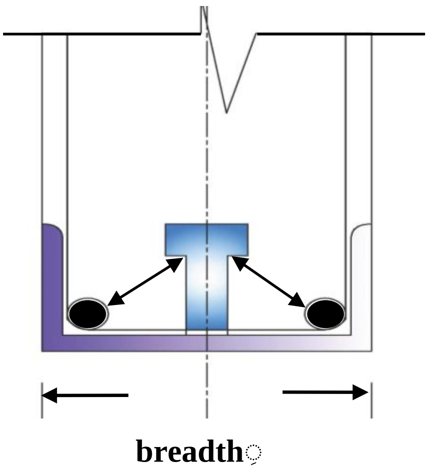


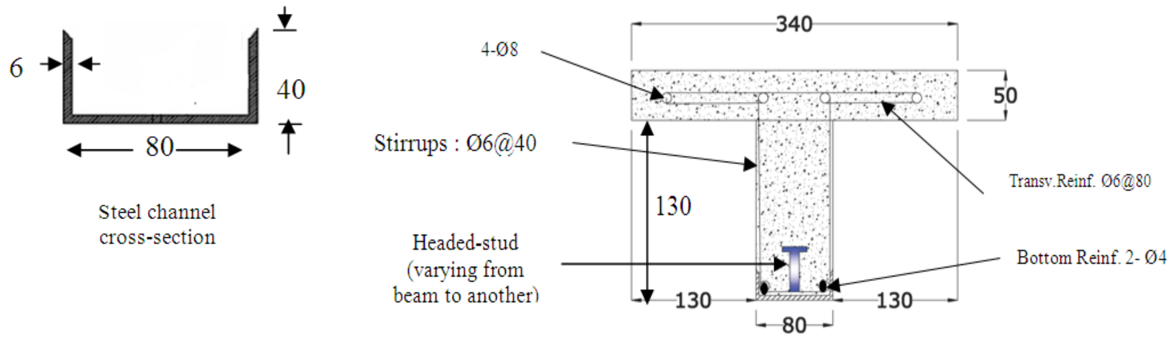
Fig. 1: Prevention of the steel channel separation due to vertical force transfer by the inclined compressive struts in concrete

The interaction described above of channel, headed studs, longitudinal reinforcing bars and transverse stirrups is clearly of complex nature. Certainly, the correct *juxtaposition* of the stud head and the longitudinal steel bar is of *paramount importance*.

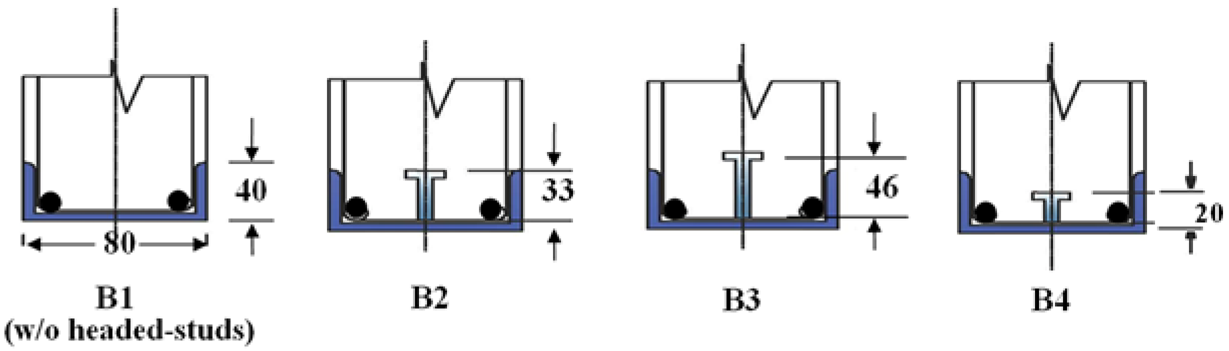
The main objective of the work presented in this paper is to experimentally determine the optimum length of the headed studs (relative to *breadth of the whole beam* and *flange width of the steel channel*) which realizes that correct juxtaposition producing the *most efficient* compressive struts defined above. In addition, experimental evaluation of the *optimum ratio* of diameter of the stud *head* to the length of the stud *shank*-which ensures avoidance of failure by excessive longitudinal cracking–is also a major demand.

4- Description of the Investigated Beams

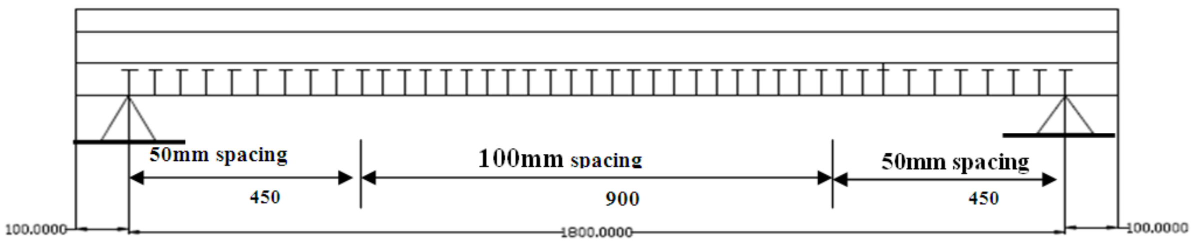
Pertinent details of the four beams tested are shown in **Fig.2**.The four beams are of the same spans, cross-sectional dimensions, reinforcement details, steel channel size and spanwise distribution of headed studs (except beam **B4** which is provided without shear connectors). Diameters of shank and head in addition to head thickness for the studs used in all beams are kept constant and equal to 8, **14** and **4 mm**, respectively. The only variable in beams **B2** to **B4** is the **length** of the shank of the shear connector. While levels of the *stud top end* and the *steel channel flange edges* are *the same* in beam **B2** (as shown in **Fig.2**), they are **different** in beams **B3** and **B4**. In **B3** the *stud top end* level is **higher** than the *steel channel flange edge* level by about **30%** of its interior width (**34 mm**). In **B4** the situation is **contradictory**. The four tested beams were made longer than their span lengths so as to ensure adequate supported distance.



Typical cross – section for each of the four tested beams



Details of the headed-studs for the four beams



Elevation of a typical beam showing distribution of the headed –stud shear connectors

Fig.2 : Details of the tested beams (All dimensions are in mm)

5- Beams Fabrication and Concrete Techniques

With reference to **Plate 1**, the headed studs were fillet-welded to the steel channel web using **E70XX** electrode. Then cages of the steel reinforcing bars were placed in the channel grooves as shown in **Plate 2** before erecting the steel-plate forms by welding and bolts. Cement mortar blocks were used as saddles to maintain correct cover. The concrete in beams was compacted with the help of an internal vibrator. Each beam was kept under **100%** humidity for **7** to **8** days then left indoors until testing.

Plate 1: Typical steel channel with its welded headed studs for a typical tested beam

Plate 2: Typical steel reinforcing bar cage resting on the steel channel (with welded headed studs) for a typical test beam.

6- Experimentation

6-1 Instrumentation and testing disposals

The test beams were subjected to a central **1 m** length uniformly distributed load applied at the top (compression) surface of the beam in a **2500 kN** capacity Universal Testing Machine (hydraulic type) of the structure laboratory in the University of Technology, Baghdad. Two series of steel I-joists with rollers, steel plates and rubber pads were employed as a load transfer device for the four beams. Details of the test set-up are shown in **Fig.3.**

Three dial gauges having the smallest divisions of **0.01** mm were employed for each test beam to measure the midspan deflections and the two relative longitudinal end slips at concrete-steel channel web interfaces at each load increment.

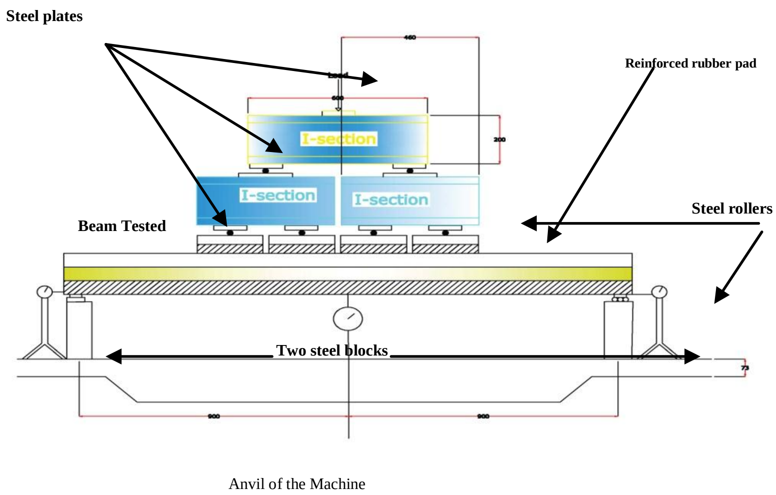


Fig.3 Test set-up for loading of beams.

The load applied to the test beam was monitored by an electric load cell placed between the loading ram and the anchorage frame. **Plate 3** shows the specified testing machine with its load cell and a typical test beam under experimental loading**.**

Plate 3: The universal testing machine (8551M.F.L.system) with a typical beam.

6-2 Control specimen and mechanical properties

According to the **B.S 1881** [15], **100 mm** reinforced concrete cubes representative to the four beams were tested for compression at age of **28** days. Corresponding values for the modulus of elasticity E_c were computed according to equation **17** page **45** in Ref**.** [16]. The mechanical properties of concrete, steel channel, headed studs and reinforcing steel bars for the four test beams are given in **Table 1**.

Table 1: Mechanical Properties of the constitutive materials of the tested beams

		Concrete (28 days age)		Reinforcing Steel Bars			Steel Channel & Headed Stud		
		f_{cu}	Ec	f_y	f_u	E_s	F_y	F_u	E_s
Beam Designatio	B1	32.78	24645	412	486	207000	248	400	200000
	B2	35.01	25638						
	B3	34.33	25390						
	B4	32.78	24645						

***All numbers are in MPa .**

7- Presentation and Interpretation of Test Results

The directly observed responses of the loading process for each of the four investigated beams are the load P_{cr} causing appearance of flexural cracking directly above level of the steel channel and the load P_u at the ultimate stage. They are given in **Table 2** shown below. The mechanically measured displacements (by deflectometers in the laboratory are the consecutively growing midpan deflections and horizontal relative end slips at steel concrete interfaces with the monotonically increasing loads applied up to failure as shown in **Fig 3**. Those measured displacements are shown in **Figs. 4** and **5**, respectively.

Table 2 : Loads at the stage of crack appearance above level of the steel channel , and at the ultimate stage for the four tested beams

Beam designation (1)	B1	B2	B3	B4
Pcr(2) kN	42	61	53	58
Pu (3) kN	49.8	83.8	57.2	83.4
Pcr/Pu	0.843	0.728	0.927	0.695

(1) with reference to Fig. 2 . (2)Applied Load at stage of crack appearance above level of the steel channel . (3) Applied load at ultimate stage .

It can be mentioned here that values of the ultimate crushing stress (characteristic strength; f_{cu}) of the concrete are not same for the four investigated beams (as given in Table **1)**. To find out the exclusive effect of the headed studs (of various lengths and dimensional proportions) on flexural behavior and integrity the observed load values are modified (then presented in **Table 3** and **Figs**. **4** and **5**) to eliminate the effect of variation in f_{cu} values. The modifications are done by multiplying the observed load value of the concerned beam by the ratio **β** obtained by the following relation:

$$\beta = \sqrt{f_{cu,1} / f_{cu,i}} \qquad \text{...............(1)}$$

where, $\mathbf{f_{cu,1}}$ = Characteristic strength of concrete of beam **B1**, $\mathbf{f_{cu,i}}$= Characteristic strength of concrete of beam $\mathbf{B_i}$ concerned , **i=1,2,3** and **4**.

Laboratory test results presented in **Table 2** and **Figs. 4** and **5** have then been interpreted to quantitively incarnate the enhancements achieved in the principal properties within the two main studied mechanical properties of *"Composite Reinforced Concrete"* beams-namely; **"Flexural Behavior"** and **"Integrity"** due to introducing headed-stud shear connectors of various lengths and dimensional proportion. Associated numerical evaluations are given in **Table 3.**

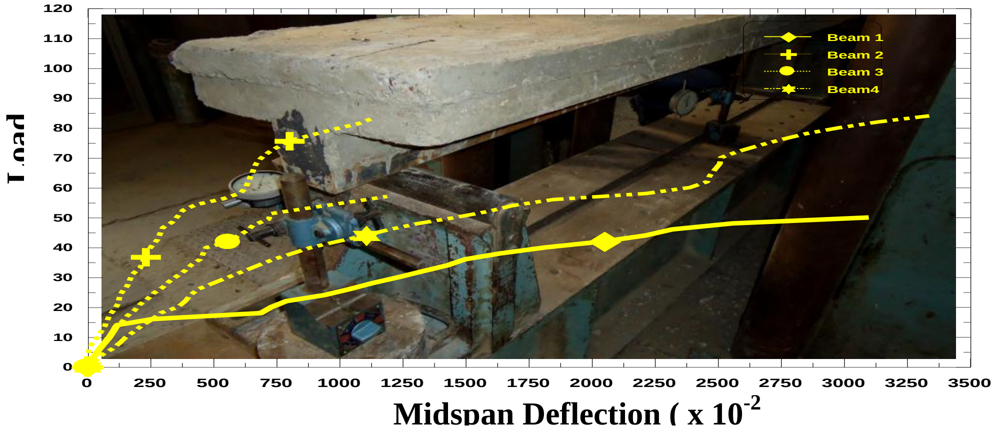


Fig. 4 : Load - midspan deflection relationships of the four investigated beams extracted from the laboratory testing programme.

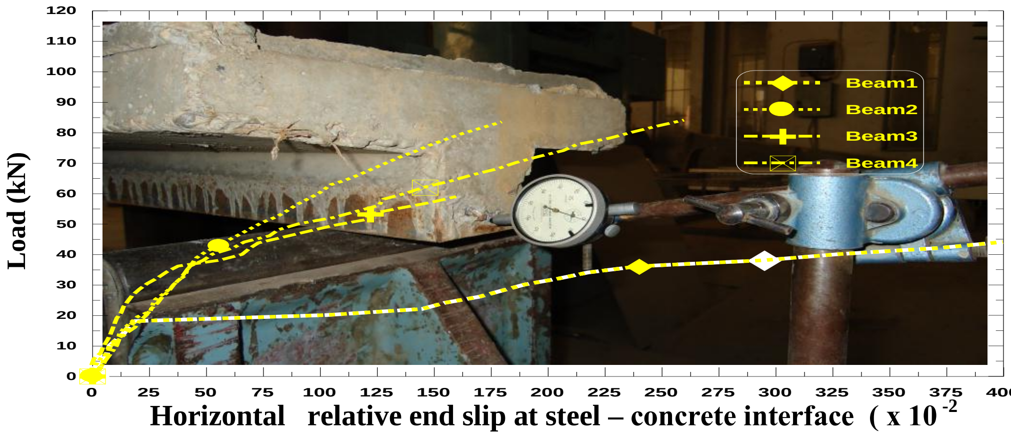


Fig. 5 : Load - relative horizontal end slip at steel –concrete interfaces relationship of the four investigated beams extracted from the laboratory testing programme.

Table 3: Comprehensive interpretation of the drawn laboratory test results for the four investigated beams

											Flexural Behavior	Integrity Characteristics	AASS(13) / AFS
Beam (1) Designation	Pu(kN)	Δ cr(2) mm	Δ u(3) mm	IFS(4) N/mm.	AFS(5) N/mm	FD(6) ratio	% ΔFD(7)	δcr(8) mm	δ u(9) mm	%PCS(10)	AASS(11) N/mm	I.I(12)	
B1	49.8	20.7	31.0	9677	1606	1.5	------	3.5	4.0	12.5%	12450	1	7.75
B2	83.8	6.3	11.5	18824	7287	1.83	22%	1.03	1.8	42.8%	46556	3.74	6.39
B3	57.2	7.8	11.8	10670	4847	1.51	0.7%	1.25	1.6	21.9%	35750	2.87	7.38
B4	83.4	22.0	33.5	7826	2490	1.52	1.33 %	1.28	2.6	50.8%	32077	2.58	12.88

(1) with ref. to Fig2 .
(2)Mid-span deflection at stage of crack appearance above level of the steel channel.
(3) Mid-span deflection at ultimate stage .
(4) Initial flexural stiffness which is equal to the initial tangent slope of the load – deflection curve shown in Fig .4.
(5)Average flexural stiffness = Pu/Δu .
(6) Flexural ductility ratio = Δu/Δcr.
(7)Percentage of increase in the FD ratio with introducing headed-stud shear connectors.
(8) Relative horizontal end slip at steel-concrete interface at stage of crack appearance above level of the steelchannel .
(9) Relative horizontal end slip at steel – concrete interface at ultimate stage .
(10)Percentage of relative end slip at steel –concrete interface at post –cracking stage = %(δu- δcr)/ δu .
(11)Average anti-slip stiffness =Pu/ δu .
(12) Integrity index , for beam Bi : I.I. = [Pu / δu] / [Pu/ δu] $_1$ ***, i= 1,2,3,4***

Final observed behavior of the loading process (after failure) is the resulting fracture pattern for which a view for a typical tested beam is given in **Plate 4** . The dominant fracture pattern is a **45^o** inclined symmetric failure surface including portions of crushed concrete in the compressed flange as shown in **Plate 4**.

Plate 4: View of a typical tested beam after failure showing the fracture pattern.

8- Discussion of Test Observations and Interpreted Measurements

Such being the state of the resulting observations and measurements, their discussion is driven herein as follows:

(I) Flexural behavior and integrity Characteristics:

Based on the numerically interpreted evaluations given in **Table 3**, an argumentum reasoning (concerning those two main mechanical properties of the four *"Composite Reinforced Concrete"* tested beams varying in *dimensions* and *geometrical proportions* of their headed studs) is driven herein within seven respects, as follows:

a) *Initial flexural stiffness*: Beam **B2** has a value which is larger by more than **80%** than the largest of the three corresponding values (which are close to each other) of the three remaining beams.

b) *Average flexural stiffness* (reflecting serviceable flexural efficiency): Again beam **B2** is clearly preeminent followed by beams **B3**, **B4** and **B1** respectively. The consecutive incremental percentages of increase (from beam **B2**.. to.. **B1**) are **55%**, **95%** and **50%** respectively.

c) *Flexural ductility*: Beam **B2** is clearly superior to the three remaining beams (which are within the same level). The former beam encompasses the remaining ones by **20%** in average.

d) *Relative interfacive slip at the two main stages*: Beams **B2** and **B3** have the minimum slippage values followed by **B4**. Their mean slip values are about **73%** and **38%** of beams **B4** and **B1** corresponding values, respectively.

e) *Percentage of relative end slip at post cracking stage*: This parameter expresses the capability of the composite beam to sustain excessive relative interfacive slip before failure (i.e. relative end-slip ductility). The three beams containing shear connectors have *otentially* larger percentage values than the corresponding percentage of beam **B4** (of no shear connectors). Specifically, beam **B4** (of the smallest length of headed studs) is of the higher prcentage, followed by beam **B2** (of the intermediate length).

f) *Average anti-slip stiffness* and *Integrity index* parameters giving indications about interface relative slippage stiffness): Clearly, beam **B2** further surpasses the other beams followed by beams **B3 and B4** (of close levels). While beam **B2's** integrity index is larger by **37%** than the mean index of beams **B3** and **B4**, the latter index value is greater than that of beam **B4** (of no shear connectors) by **172.5%,** thus reflecting the *vital role* of the headed studs in constraining relative slip at steel-concrete interfaces then raising the integrity characteristics of such *"Composite Reinforced Concrete Beams"*.

g) *Ratio of "Integrity to flexural stiffnesses*": Beams **B1**, **B2** and **B3** have close values of this ratio and each of them is smaller by **60%** than the corresponding ratio of beam **B4** (having the shortest headed studs). This expresses the major effect of the headed stud shank length increasing its *relative* anti-slip stiffness.

(II) Mode of failure

All of the tested beams failed due to compression failure. Here concrete crushing occurred at some points in the flange within the central compression zone directly beneath the **1 m** length uniformly *distributed* load (resembling the fracture patteren obtained in a previous experimental investigation on beams of the same type [2]. A symmetric two-sided inclined, fracture surface began at each of the two ends partial uniform load.
Although flexural cracks developed first in all of the beams, tensile flexural failure was not the find mode of the failure in any of the test beams. Fracture surface began each of the two ends of the partial uniform load. Although flexural cracks developed first in all of these beams, tensile flexural failure was not the final mode of failure in any of the test beam.

9- Conclusions

Recalling the main objective concentrating on the optimum relative length of the headed studs in reinforced concrete T-beams cast in steel channel, it has been found that the case of a headed stud of length equal to the steel channel flange width and half the breadth of the whole T-beam B2 is superior to the two other cases containing headed studs of lengths larger and smaller than the steel channel flange width by 30% (cases of beams B3 and B4, respectively), in addition to the case **B1** of no headed studs. The *stud head-longitudinal steel bar juxtaposition* furnished in beam **B2** has given the highest performance in *flexure* and *integrity* since it produces the most efficient *interactive compressive struts* (shown in **Fig.1**) of about ***45^{o}*** *inclination*.

In summary, following concluding remarks can be drawn regarding the aspects of privilege for the case of moderate length headed studs relative to the other studied cases:

1) *Flexural stiffness*: In the linear (pre-cracking) stage, the case of moderate headed- stud length gives flexural stiffness much higher than each of the stud-containing comparative cases. This preeminence grows gradually with load increase till failure where it exceeds **200%** for the *average* flexural stress.
2) *Ultimate flexural capacity*: The two cases of *moderate* and **30%** *shorter* stud lengths posse's ultimate flexural resistances larger (by about **50%**) than that of the **30%** longer stud length, thus detecting the weakening in the *lateral* performance of the rather long headed stud. On the other hand the case destitute of headed studs undergoes early failure.
3) *Flexural ductility*: The favorite case of moderate-length headed studs reveals more than **20%** higher flexural ductility than each of the two cases containing extravagant-length headed studs.
4) *Relative end-slip extension*: The moderate - length and the long headed- stud cases give so specified slip values that are about **two-thirds** and **one-thirds** of those given by the short stud and the free- off-stud cases, respectively.
5) *Relative end slip ductility*: Much higher levels of the specified ductility are attained by the three stud-containing cases than that of the case without headed studs, with the moderate length and the short headed-stud cases being advanced.
6) *Integrity level*: A **30%** rise in this index is achieved when short or long headed - studs are replaced by ones of moderate length. On the contrary, removal of the headed studs from reinforced concert T-beam cast in steel channel causes a drastic drop in that index (of about **two-thirds** of the recently achieved level) although the concrete at the level of shear connectors is confined with the channel which prevents it from bursting outwards.

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