

Experimental Comparative Study on Composite RC T-Beams Behavior with Diverse Distributions of Headed Studs in Sagging –Moment Tensioned Concrete Media

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Abstract

With the purpose of evaluating the influence of both the numbers and configurations of headed-stud shear connectors in simply supported reinforced concrete T-beams of webs partially cast in and interconnected to steel channels at their soffits , an experimental program was carried out using three cases of studs quantities and distributions in addition to the control free-of-stud case . The beam of moderate non-uniform stud distribution of interior spacing not less than the T-beam breadth reconciled the prevalent advantages of the two other beams embracing uniformly distributed few and abundant studs separately ,whilst eliminating their probable defects. Specifically, respects of the defined favorite beam merit are : the flexural stiffness ,ductility and ultimate resistance in addition to the relative - slip constraint and integrity characteristics. Despite 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 - beam , Steel Channels , Shear Connector Distribution ,Uniform Loading, Cracking Load ,Ultimate Load, Fracture Pattern.

دراسة عملية مقارنة لعتبات مركبة خرسانية مسلحة بمقطع T لتوزيعات متنوعة للأوتاد المزودة برؤوس في الأوساط الخرسانية المشدودة للغزوم الموجبة

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الخلاصة

لغرض تقييم تأثير أعداد ونمط ترتيب روابط القص الوتدية ذوات الرؤوس في العتبات الخرسانية المسلحة بسيطة الارتكاز ذوات الوترات المصبوبة جزئياً والمرتبطة داخلياً بحديد ساقية عند أسطحها السفلى ، تم تنفيذ مناهج تجريبي باستخدام ثلاث حالات من أعداد الأوتاد وتوزيعها إضافة إلى حالة السيطرة الخالية من الأوتاد . لقد تبين إن حالة العتبة الحاوية على عدد معتدل من الأوتاد وغير متجانسة التوزيع بمسافات داخلية بين الأوتاد لا تقل عن عرض وترة العتبة تجمع المزايا السائدة للعتبتين الأخرتين اللتين تضمنان أوتاد متجانسة التوزيع إحداهما غزيرة والأخرى متباعدة مع نحاشي عيوبها المحتملة . على وجه التحديد ، فإن مجالات أفضلية العتبة المثلى هي : الجساءة والمطاوعة والمقاومة القصوى الإنشائية ، إضافة إلى تقييد الانزلاق النسبي وخصائص الوحدة التمامية . رغم احتجاز الخرسانة في نطاق حديد الساقية ، فإن انخفاضات حادة في مستويات مقاومة الانحناء القصوى والوحدة التمامية قد حصلت عند إزالة روابط القص .

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Introduction

General Statement and Review:

This investigation is a part of larger study on the behavior and constitutional geometry and proportioning of *Composite Reinforced Concrete*. The latter is a specific structural material combination which reconciles the *material advantage of reinforced concrete* with the *constructional advantages* of the *normal composite construction* whilst eliminating some of their attendant disadvantages. Its simplest status is represented by a reinforced concrete T-beam of web partially cast in a steel channel and interconnected by headed studs welded to steel channel web. As the steel - channel centroid is very low ,quite near the soffit(when compared with the case of steel I-section interconnected to an upper concrete slab) , giving a lever arm which is a high proportion of the full depth , the cross-sectional area of the steel section is thereby reduced .This reduction is accompanied by a similar reduction in the number of shear connectors which is proportional to the former quantity. *Thus , composite reinforced concrete is reinforced concrete with external reinforcement.* From the constructional standpoint, *composite reinforced concrete* beams have the same *normal composite construction* advantage of improving the speed of construction which stems from the use of mild steel content of the beam to support precast concrete units and as a form for the concrete part soffit of the composite beam . The early experimental and theoretical studies of composite reinforced concrete beams were begun by **Taylor** in **1972** (cited in Ref. [1] , pp. 8-11). Frequent studies about this objective were then recommenced in **1973** and continued till **1980** by **Taylor et al.** , [2 , 3 , 4 , 5 , 6 , 7] which were directly followed by **Taylor's** final evidence in **1980** about advantages , drawbacks and precautions of composite reinforced concrete beams [8] .

After the campaign of **Taylor** and his **partners** , no published work in *this specific field of reinforced concrete (i.e composite reinforced concrete)* has been met other than the few researches achieved in **Iraq** , two of which were in the eightieth of the elapsed century [9 , 10], and other three are in the precedent decade [11 , 12 ,13] .

Behavior of Headed Studs Embedded in

Tensioned Concrete Media:

In *normal composite construction* - consisting of interconnected steel I-section and top concrete slab - the general performance of connectors was found to be better when the slab is in compression than in tension(as in the case of bending of a composite beam under hogging moment) [14] , since the compression in the slab increases the connector stiffness . When the slab is in tension, the connection is less stiff and of less ultimate strength. It was therefore proposed [15] for *normal* composite beams in buildings that the ultimate strength of shear connectors in negative moment regions of continuous beams should be taken as **20%** less than the value used for positive moment regions. Regardless whether the embedment concrete medium is tensioned or compressed the concrete around the holding down force (provided by the underside of the stud head to resists uplift at interface)should be effective in resisting the created tension . Furthermore ,tests showed that the fatigue life of headed studs embedded in tensioned concrete is less than that of identically loaded connectors embedded in compressed concrete [16] .The situation for headed stud behavior in tensioned concrete media of *composite reinforced concrete beams* is rather different from two contradictory standpoints . First the stud - embedment tensioned concrete media is at the *sagging* moment regions definitely created at midspans representing the severest cases in the widely used

simply supported reinforced concrete T - beams of webs partially cast – at their soffits –in steel channels . Secondly, the tensioned concrete at the level of the shear connectors is confined within the steel channel and cannot burst outwards (as in the case of haunched deep normal composite beams) .

Research Significance

The two surveys , reviewed above , of previous work on composite reinforced concrete , and on headed studs embedment in tensioned concrete media have shown that two phenomena concerning role of headed studs in *composite reinforced concrete* not yet be fulfilled by research :

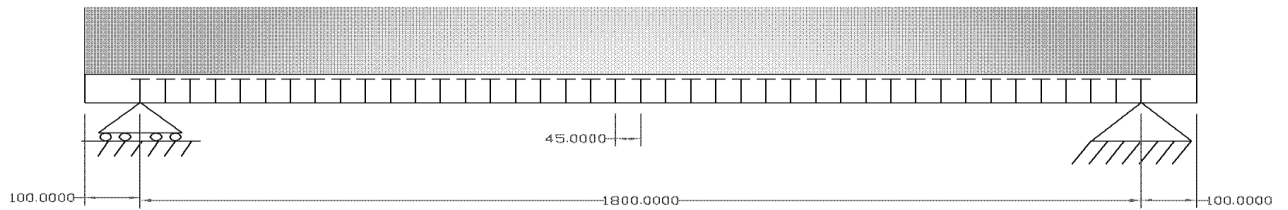
1- Behavior and efficiency of headed studs in composite reinforced concrete accounting for the two specialized contradictory factors stated in the previous section. It is a complicated problem and no work on this has so far been pursued. However a pioneering attempt has been recently accomplished [17] .

2- The optimum distribution of headed studs in composite reinforced concrete and whether it is of uniform span wise spacing or not .The defined optimum spacing (research objective) of the headed studs is that leading to **simultaneous stud failure (fracture of the weld collar at the stud root or excessive flexural and shear deformation of the stud shank) and crushing of the compression zone concrete at midpans** of simply supported reinforced concrete T - beams of webs partially cast in and interconnected to steel channels at the T - beams soffits. It must be noted that four beams were tested by **Taylor [1]** in which the only variable was the position and spacing of the studs . However there was no apparent effect within the range of the tested spacings of studs. Although two beams failed in flexure and two in shear , all beams failed at approximately the same load .*The present study is an attempt to evaluate the effects of the stud distribution in composite reinforced concrete beams then determine the optimum one .*

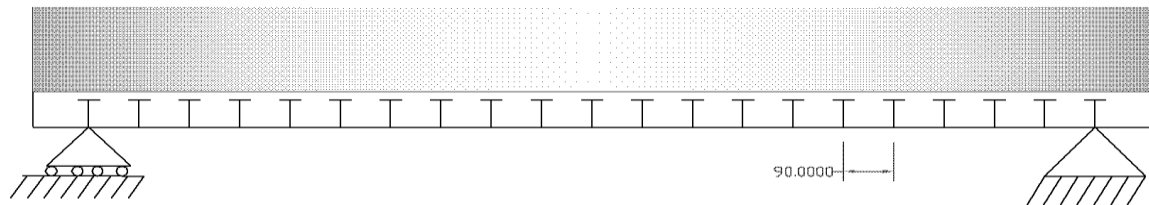
Experimental Programme

Beam Prototypes:

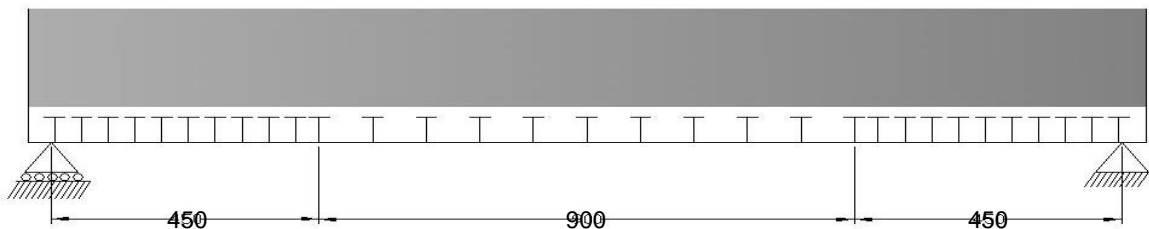
Pertinent details of the four beams tested are shown in **Fig.1**.The four beams are of the same spans , cross - sectional dimensions ,reinforcement details, and the steel channel size used . The shear connectors used are all of headed - stud type (except beam **TB-Ø** which is without shear connectors) and are all identical in their dimensions (head diameter and thickness, and shank diameter and length)as shown in **Fig .1**. The only variable in beams **TB-U45** ,**TB-U90** and **TB-NU45/90** is the spanwise distribution of headed studs .The stud distributions for beams **TB- U90** and **TB- NU45/90** are uniform and of **45** and **90** mm spacing's, respectively, whereas non-uniform stud distribution is used for beam **TB-NU45/90** represented by **90** mm spacings at the beam mid-half and **45** mm spacings at its two end quarters.



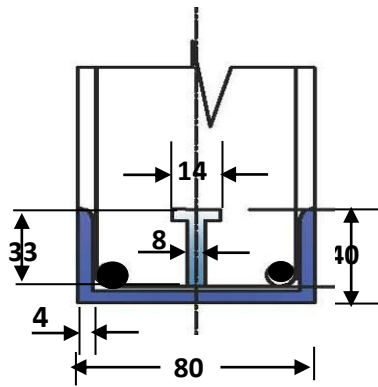
Beam TB-U45 (uniform headed – stud)



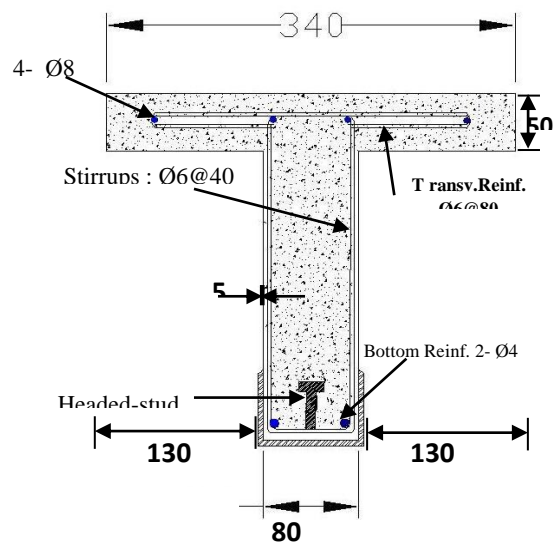
Beam TB-U90 (uniform headed - stud spacing)



Beam TB-NU45/90 (non-uniform headed - stud spacing)



Details of the steel channel and the headed studs (for beam TB- Ø studs are eliminated)



Typical cross – section for each of the four beams (for beam TB- Ø studs are

Fig.1: Details of the tested beams (All dimensions are in mm)

Constitutional Properties

According to **B.S.1881[18]** ,100 mm concrete cubes representative to the four beams were tested for compression at age of **28** days . Corresponding values for the modulus of elasticity **Ec** were computed according to **Eq.17**, page **45** in Ref.[19]. The mechanical properties of the concrete, steel channels, headed studs and reinforcing steel bars for the four beams are given in **Table 1**.

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

Beam Mark		Concrete (28 days age)		Reinforcing Steel Bars			Steel Channel and Headed Studs		
		fcu	Ec	fy	fu	Es	Fy	Fu	Es
Beam Mark	TB-Ø	32.8	24645	412	486	207000	248	400	200000
	TB-U45	33.1	24784						
	TB-U90	35.5	25856						
	TB-NU45/90	35	25638						

(All numbers are in MPa)

Fabrication and Casting

By scrutinizing Plates **1** to **3** (which show the steel channels with their attached headed studs for beams **TB-U45**, **TB- U90** and **TB- NU 45/90** , respectively) it is seen that the headed - stud shear connectors have fillet - weld collars at their roots to fix them firmly to the steel channels webs . The cages of the steel reinforcing bars are placed in the channels grooves , as shown in **Plate 4** , before erecting the steel - plate form 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 .



Plate1: The steel channel with its attached headed studs for beam **TB –U45**



Plate 2: The steel channel with its attached headed studs for beam **TB-U90** .



Plate 3: The steel channel with its attached headed studs for beam TB-NU45/90 .



Plate 4: The steel reinforcing bar cage resting on the steel channel (with welded headed studs) for a typical test beam .

Test Setup:

The test prototypes were subjected to a central: 1- m length uniformly distributed load applied at the top (compression) surface of the prototype by a 2500-kN capacity Universal Testing Machine (hydraulic type) of the Structure Laboratory in 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 prototypes .Details of the test setup are shown in Fig.2 . Three dial gauges of 0.01 mm sensitivity were employed for each test prototype to measure the mid span deflection and the two relative longitudinal end slips at concrete - steel channel web interfaces at each load increment.

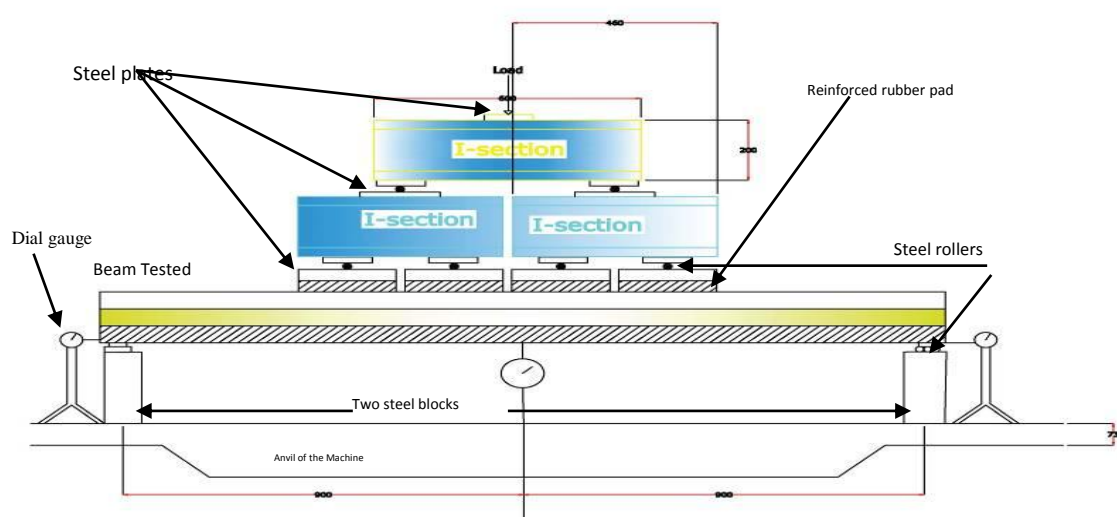


Fig.2 : Test set –up for loading of beams

The loads applied to the test beams were monitored by an electric load cell placed between the loading ram and the anchorage frame .Plate 5 shows the specified testing machine with its load cell and typical test beams under experimental loading



Plate 5: The universal testing machine (8551M.F.L.system) with a typical test beam

Presentation and Analysis of Test Responses

The mechanically measured displacements (by deflect meters) in the laboratory are the consecutively increasing midspan deflections and the horizontal relative end-slips at steel-concrete interfaces with the monotonic increasing loads applied up to failure as previously shown in **Fig.2**. Those measured displacements are shown in **Figs. 3** and **4**, respectively.

The directly observed responses of the loading process for each of the four tested 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**.

It may be noticed here that values of the $\beta = \sqrt{f_{cu,\emptyset} / f_{cu,i}}$ ultimate crushing stress (i. e .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 effects of the headed studs amounts and distributions on flexural behavior and integrity the observed load values are modified (then presented in Table 2 and Figs .3 and 4) 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:

where:

$f_{cu,\emptyset}$ = Characteristic strength of concrete of beam TB- \emptyset

$f_{cu,i}$ = Characteristic strength of concrete of the other beam TB-i concerned, $i = U45, U90$ or NU45/90.

Laboratory test results presented in Figs. 3 and 4 have then been interpreted to quantitatively bring out 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 amounts and distributions. Associated numerical evaluations are given in Table 2.

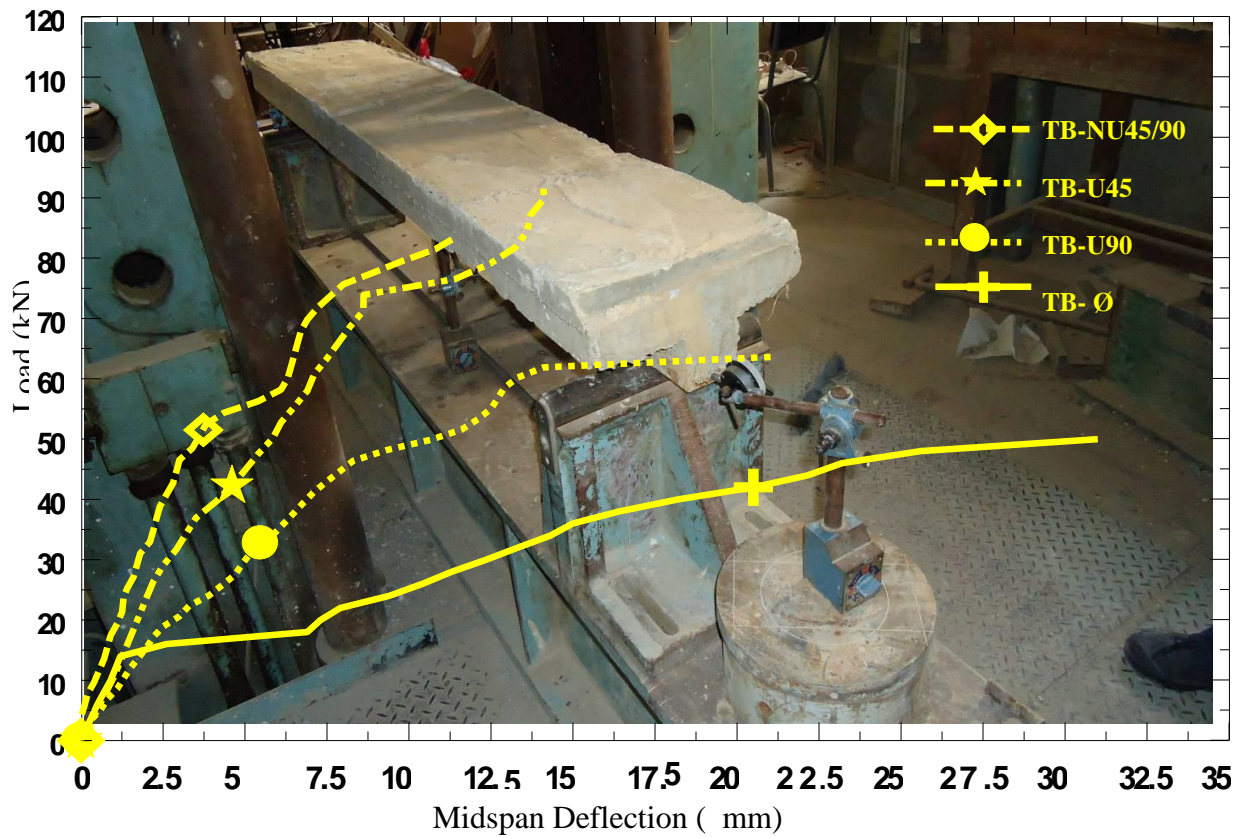


Fig. 3 : Load ~ midspan deflection relationships of the four tested beams

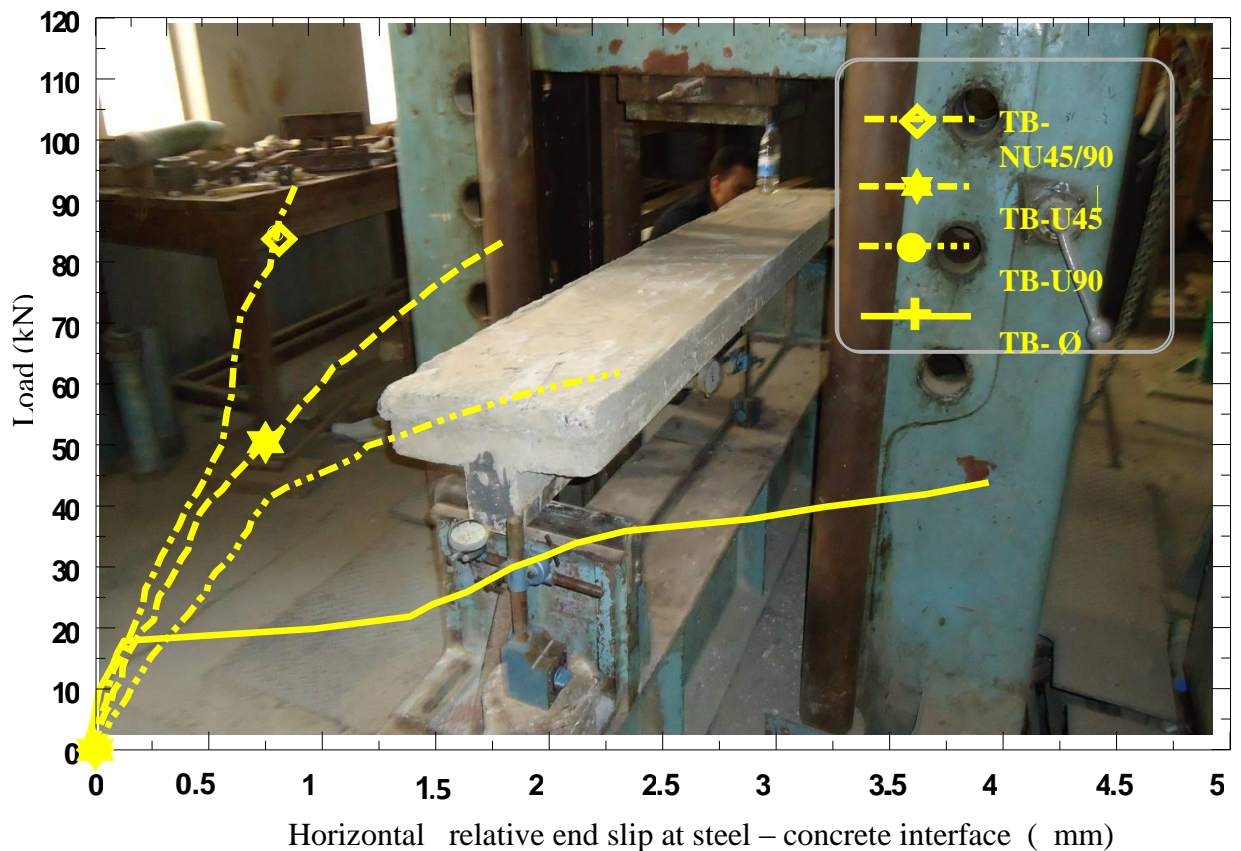


Fig. 4 : Load ~ relative horizontal end slip relationships of the four tested beams

Table 2 : Comprehensive analysis of the drawn laboratory test results for the four investigated prototypes

Beam Mark ⁽¹⁾	Flexural Behavior							Integrity Characteristics					AASS / AFS		
	P _{cr} ⁽²⁾ KN	P _u ⁽³⁾ KN	P _{cr} / P _u	Δ _{cr} ⁽²⁾ mm	Δ _u ⁽³⁾ mm	IFS ⁽⁴⁾ N / mm	AFS ⁽⁵⁾ N / mm	FD ⁽⁶⁾ ratio	%ΔFD ⁽⁷⁾	δ _{cr} ⁽⁸⁾	δ _u ⁽⁹⁾	%PCS ⁽¹⁰⁾		AASS ⁽¹¹⁾ N/mm	IT ⁽¹²⁾
TB-Ø	42.4	49.8	0.85	20.7	31	9677	1606	1.5	-----	3.5	4	12.5%	12450	1	7.75
TB-U45	75.7	92.6	0.82	9.8	14.9	17129	6215	1.52	1.33%	0.69	0.88	21.6%	105227	8.45	16.93
TB-U90	50.9	63.7	0.8	11.3	21.2	8130	3005	1.88	25%	1.17	2.31	49.4%	27576	2.21	9.18
TBNU 45/90	67.2	83.8	0.8	6.3	11.5	18824	7287	1.83	22%	1.03	1.8	42.8%	46556	3.74	6.39

- (1) with reference to Fig 1.
- (2) Applied load and midspan deflection at stage of crack appearance above level of the steel channel.
- (3) Applied load and midspan deflection at ultimate stage
- (4) Initial flexural stiffness which is equal to the initial tangent slope of the load – deflection curve shown in Fig .3.
- (5) Average flexural stiffness = P_u/Δ_u.
- (6) Flexural ductility ratio = Δ_u/Δ_{cr}.
- (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 steel channel .
- (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 = % (δ_u - δ_{cr}) / δ_u .
- (11) Average anti-slip stiffness =P_u/δ_u .
- (12) Integrity index , for beam TB-i concerned I.I [P_u/δ_u]_{beam TB-i} / [P_u/δ_u]_{beam TB-O} , i = A, L or M

Subsequent observed behavior of loading process (after failure) is the resulting fracture pattern- for which a view for a typical tested beam is given in **Plate 6** . The dominant fracture pattern is a 45° inclined symmetric failure surface including portions of crushed concrete in the compressed flange of the T-beam . The last observation was made after total removal of the concrete and steel reinforcing bar cages of the prototypes **TB-U45**, **TB-U90** and **TB-NU45/90** to inspect the status of headed studs after failure . With reference to **Plate 7** It has been noticed that only the twenty headed studs of prototype **TB-U90** underwent obvious flexural and shear deformation in their shanks.



Plate 6: View of a typical tested beam after failure showing the fracture pattern



Plate 7: The steel channel and the attached headed studs of the damaged beam TB-U90 after removal of reinforced concrete , showing deformations of the studs .

Discussion of Measured and Observed Responses

Measured Response

They are represented by load- midspan and load-relative end slip relationships exhibited in **Fig.3** and **4**, respectively.

Inspection of those two figures lead to the following remarks :

1- Comparison of the two relationships of beam **TB-Ø** (without shear connectors) and **TB-U90** (of few uniformly spaced headed studs) shows that introducing this amount of headed studs increases the cracking load P_{cr} and the ultimate load P_u by **20%** and **28%** , respectively.

2- On doubling the number of headed studs of beam **TB-U90** (to obtain the case of beam **TB-U45** of abundant uniformly spaced studs) large increases –as high as **49%** and **45%** - are gained in values of P_{cr} and P_u (relative to beam **TB-U90** values) , respectively. .

3- When half the number of headed studs in middle half of beam **TB-U45** are eliminated –to obtain the case of beam **TB-NU45/90** of distant interior studs and close exterior ones - (thus reducing the total number of **TB-U45** studs by **25%**) small decreases – as low as **11%** and **9.5 %** -are gained in values of P_{cr} and P_u (relative to beam **TB-U45** values) , respectively .

4- If the ten studs at each of the two quarter ends of beam **TB-NU45/90** are reduced to five (to obtain the case of beam **TB-U90**) thus decreasing the total number of beam **TB-NU45/90** studs by **33.3%**, moderate decreases (of **24%**) occur in values of P_{cr} , P_u (relative to beam **TB-NU45/90** values) .

5- Additionally, the typical load- midspan deflection curve of beam **TB-NU45/90** till failure exhibited in **Fig.3** is examined. Generally, it can be subdivided into two ranges: -*First range (serviceability state)*: in which the load increases almost linearly up to about **80%** of the failure load. The horizontal shear force acting at the steel- concrete interface is transmitted principally by the stud root. Because of the load concentration at the weld collar, only small deformations take place referring to *full* shear connection. - *Second range*: where nonlinear increasing of deformation is observed referring to loss of stiffness caused by the local crushing of the concrete around the *stud base leading to a load distribution from the weld collar to the stud shank*. This results in flexural and shear deformation of the studs wholly depending on the **E**-modulus of the concrete.

6 - Attentive consideration of **Figs 3** and **4** gives distinct recognition of the trends in curves of the two relationships for each beam. While the transition from beam **TB-U45** situation to that of beam **TB-NU45/90** gives very slight change in flexural stiffness (announced by deflection) it certainly creates very large increase in horizontal relative end slip (which potentially refers to lowering in the degree of partial interaction) reaching **100%** at failure of those two beams. Such huge differences are not recognized with probable transitions between any other two situations of the four tested beams.

Observed Responses

1. Mode of failure:

All of the tested prototypes failed due to compression failure. Here concrete crushing occurred at some points in the flange within the flange central compression zone directly beneath the **1-m** length uniformly distributed load (resembling the fracture pattern obtained in a previous experimental investigation on beams of the same type [2]). A symmetric two-sided inclined fracture surface begun at each of the two ends of the partial uniform load.

2- Status of the headed studs at failure

The recognized flexural and shear deformations *only* in shanks of the headed studs of the beam of the fewest number of headed studs (beam **TB-U90**) means that the ultimate strengths of the headed studs of the two other provided beams **TB-U45** and **TB-NU45/90** have not been reached yet.

Discussion of Analyzed Results

Based on the numerically interpreted evaluations given in **Table 2** an argumental reasoning concerning those two mechanical properties of the four "composite reinforced concrete" tested beams varying in *amounts and distributions* of their headed- stud shear connectors is driven here within two aspects, as follows:

Flexural Behavior

1-*Initial flexural stiffness*: beams of abundant and moderate numbers of headed studs (**TB-U45** and **TB-NU45/90**, respectively) have close and large values which are more than twice those of the two other beams (of few and no headed studs).

2- *Average flexural stiffness*: Beam **TB-NU45/90** has the largest value (even than that of beam **TB-U45**). Value for each of the two stiff beams is more than twice the value for beam **TB-U90** and four times the value for the studless beam.

3- *Flexural ductility*: The two beams of few and moderate studs revealed high flexural ductility encompassing the close values of the two other beams by more than **20%**. The

constrained flexural ductility of the beam with abundant studs is attributed to the high over – required total lateral stiffness of the contained studs.

Integrity Characteristics:

1-*Relative interactive slip at two main stages* : The two beams of abundant and moderate numbers of studs have the minimum slippages ,followed by the beam of few number of studs. The main slip values of the former two beams are about **63%** and **29%** of the values for the latter beam and the studless beam , respectively . .

2- *Percentage of relative end slip at post- cracking stage* : This parameter expresses capability of the composite beam to sustain excessive relative interface slip before failure . The two beams comprising few and moderate numbers of studs have the largest percentages ,followed by the beam of abundant studs which in turn has a percentage larger by **73%** than that destitute of studs.

3- *Average anti-slip stiffness and integrity index*

They are parameters giving indications about interface-relative slippage stiffness. Clearly, beam **TB-U45** (of abundant studs) fatherly encompasses the other beams, followed by the beam of moderate number of studs (whose value is **44%** of the former beam) Meanwhile ,the beam of few studs(in the 3rd rank) has an index value greater by **121%** than that of the studless beam . These numbers reflect the vital role of the amount and distribution of the headed studs in constraining relative slip at steel –concrete interfaces then raising the integrity characteristics of *composite reinforced concrete beams*.

4- *Ratio of integrity to flexural stiffnesses* :

Beam **TB-U45** (of abundant studs) has the largest ratio which is larger by **85%** than that of few studs (coming in the **2nd** rank). This expresses the major effect of the number of shear connectors in increasing the relative stiffness of constraining slip.

Conclusions

It is recalled that the present work pertains effects of a mounts and distribution of headed studs welded along webs of steel channels integrated to RC T-beam at their web-soffits, then determining the studs optimum configurations. Specifically ,it has been found that the moderate number of studs distributed in a manner giving interior spacing not less than the web width of the T-beam, and half value for exterior distribution reconciles the advantages of the two extravagant stud distributions (the few – and the abundant uniformly distributed stud cases) ,whilst eliminating most of their attendant disadvantages .

Based on the test results, the following conclusions –regarding the facets of merits acquired by the optimum moderate headed studs distribution defined above –can be drawn :
1-*Cracking and ultimate lateral loads*: Transition from the case of distant stud distribution (lower bound)to the case of moderate non-uniform stud distribution causes 49% and 45%increases in the cracking and the ultimate lateral load values, respectively. Oppositely, transition from the situation of the stud distribution upper bound to the moderate distribution causes slight decreases in the defined stage loads not exceeding **11%**, whilst reducing stud quantity and cost by **33%**.

2 – *Flexural stiffness* : The moderate non-uniform stud distribution attains initial and average flexural stiffnesses that are higher than the corresponding ones given by the case of abundant studs by **10%** and **17%** respectively ,and higher than those given by the case of few and distant studs by **132%** and **143%**,respectively.

3-*Flexural ductility*: The moderate non- uniform stud distribution realizes , the high ductility ratio attained by the case of few distant studs .Moreover, ductility ratio of the moderate non – uniform stud distribution is higher than that of abundant studs by more than **20%** .

4 –*Relative end- slip extension* : The moderate stud distribution case gives so –specified relative –slip value equal twice the corresponding value of the abundant –stud case ,and **78%** of the value given by the case of few and distant studs .

5-*Relative end- slip ductility* : Much higher levels of this specified ductility are attained by the three stud –containing cases than the case destitute of studs ,with the moderate non-uniform and the few distant studs cases being advanced .

6- *Integrity level*: While a **69%** rise of this index is achieved by transition from the few distant studs case to the moderate non- uniform studs one, a **56%** drop in the same index accures with lessening studs number from **40** to **30**.

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