Behavior of Steel- Lightweight Concrete Composite Beams with Partial Shear Interaction

Fareed Hameed Majeed
Civil Engineering Department, University of Basrah
fhmfareed@gmail.com

Abstract

This experimental work along with an analytical analysis is investigated. The behavior of simply supported steel beams with lightweight and normal concrete slab that have the same compressive strength and slump was studied. Eight specimens tested under mid-point load and analysis by plastic analysis theory. Four of composite beams have a steel I-section beam with normal concrete slab and the other four with lightweight concrete slab. Different degrees of shear interaction were considered (100% to 40%). It was observed that there are no essential differences between the modes of failure that appeared in the tested composite beams with normal and lightweight concrete. Also, it was noted that there is a decrease in the initial stiffness and also in the ultimate strength of the composite beams when the concrete of the flanges for the tested specimens was replaced from normal to lightweight concrete for different degrees of shear connections. The analytical results for all tested beam specimens, except that with normal concrete and 100% degree of shear interaction, gave overestimate results compared with those of experimental results.

Keywords: Composite Beam, lightweight, Shear Connection, Interaction, Concrete Design

الخلاصة

يتناول هذا البحث دراسة تجريبية وتحليلية لمعرفة سلوك العتبات المركبة من مقاطع حديدية ذات الاسناد البسيط مربوطة الى بلاطات خرسانية خفيفة الوزن واعتيادي الوزن بنفس مقاومة الانضغاط الخرسانية والهطول. تم فحص ثمان نماذج معرضة لحمل خارجي مركز في منتصف طول العتبة وكذلك تم تحليلها باستخدام نظرية التحليل اللدنة. اربع من النماذج تتكون من عتبة حديدية ذات مقطع I وسقف من البلاط الخرساني الاعتيادي NC والاربع البقية بسقف من البلاط الخرساني الخفيف الوزن LC. تم استخدام درجات ربط قص (100٪ الى 40٪) لكلا النوعين من العتبات المركبة. وجد خلال فحص النماذج انه لا توجد اختلافات جوهرية بين انماط الفشل التي ظهرت في اختبار NC و LC. كما وجد ان الصلابة والمقاومة القصوى للعتبات المركبة NC تقل لنفس العتبات ذات نفس الدرجة من الاتصال باستخدام خرسانة خفيفة الوزن LC. أظهرت المقارنة بين نتائج التحليل النظري و نتائج الاختبارات العملية بانها تعطي قيم عالية لجميع النماذج فيما عدا نموذج العتب المركب من الخرسانة الاعتيادية ذو درجة تداخل 100%.

الكلمات المفتاحية :- العتبات المركبة، خرسانة خفيفة الوزن، درجة تداخل القص، التصاق، تصميم الخرسانية

1. Introduction

Steel-concrete composite beams are usually constructed from steel sections connected to concrete slab by using shear connectors at the top of steel beam to achieve composite interaction to concrete slab. One of the used shear connectors is called studs. The studs welded to the top of steel beam preceding to placing the concrete. According to these shear connectors, the steel beam and concrete slab act together structurally by providing a sufficient longitudinal shear connection between them. The most benefits of using composite structure are speed of construction, shallower construction, easy installation of services. The use of lightweight concrete for the slab of composite beam adding another benefit by reducing the weight and cost of the structure. In the past years, most of the researches have been investigated the behavior of composite beams subjected to different loads action. Vinay *et.al.*,2015, were studied experimentally eight simply supported beams which subjected to two-point loads to investigate the flexural behavior. The composite beam is steel channel section at bottom of reinforced concrete beam. Two beams were control beams without steel channel and the remaining six beams were composite beams. The results showed that, the load carrying capacity of the composite beams were increased by 38.09% to 214.28% when compared to control beams. The mid span deflection at ultimate load of the tested composite beams were reduced by about 50%. Also, they observed that, the all tested composite beams failed due to shear-compression failure in the shear span. Přivřelová,2014, were studied theoretically four models subjected to distributed load 5 KN by using finite element method to find the most adequate numerical model of a simply supported composite beam of steel I- section IPE 300 and concrete slab of normal and lightweight concrete (2 m width and 100 mm hight). He indicated that, the modeling of the steel beam as 3D element and concrete slab as a contact surface will give a good agreement compared with the manual calculations.

Eight steel-concrete composite beams were experimentally tested and theoretically analyzed in the present study in order to investigate the effect of using lightweight concrete slab LC instead of normal concrete slab NC on the behavior of partially shear connection composite beams. The two groups, LC and NC, designed with same concrete compressive strength and slump. The partial shear interaction between the steel beam and concrete slab was considered by using different degrees of shear connections DSC (100%, 80%, 60%, 40%) for each group of specimens.

2. An experimental program

2.1. Materials properties

Eight composite beams were constructed in the present work, four beams with normal concrete slabs, and the others with lightweight concrete slabs. The typical cross section of the tested composite beams is shown in Fig. 1. Where, the used materials to fabricate these tested beam specimens were concrete slab, structural steel beam, reinforcing steel, and shear connectors.

2.1.1. Concrete

Normal concrete NC and lightweight concrete LC were designed, with the same compressive strength and slump, for the slabs of tested composite beams. The materials that were used included ordinary Portland cement OPC, crushed natural gravel G, sand S, water W, Sika lighcrete (Foaming agent) FA and Superplasticizer SP. The details and results of the adopted concrete mixes are shown in Table 1.

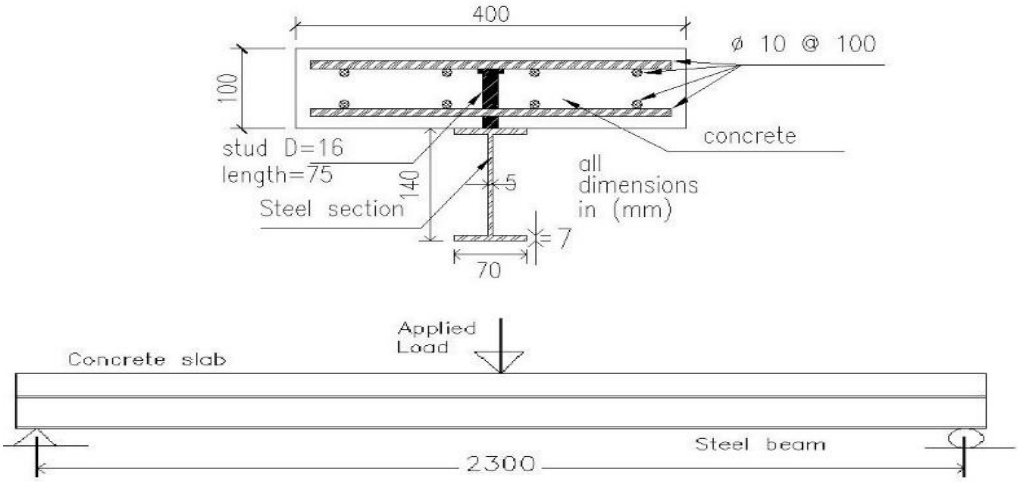

Fig.1 Details of Tested Composite Beams

Table 1 Details and results of concrete mixes

Concrete Mix Design	Weight of used materials for mixing						Slump mm	Concrete Density Kg/m^3	Cube strength N/mm^2	
	OPC Kg	S Kg	G Kg	W Kg	FA Kg	SP Kg			7-day	28-day
NC	380	600	1200	180	---	----	125	2310	18.6	24.5
LC	410	400	800	106	8	8	125	1690	19.3	24.2

2.1.2. Structural steel I-section

The steel I/wide flange 140x70x5x7 with dimensions (140 mm outside height, 70 mm top and bottom flange width, 7 mm top and bottom flange thickness and 5 mm web thickness) were used in the fabrication of composite tested beams, as shown in Fig.1. The properties of the used steel were determined from the tensile test results for coupons that taken from the flange and web of the used I-section steel beam. Table 2 shows the test results and the considered standard.

Table 2 Tensile test results of I-section steel beam

Test Specimen Location	Flange	Web	Average Value (MPa)	ASTM A 36/A 36M Requirement
Yield Stress (N/mm2)	260	260	260	250 Min
Ultimate Strength (N/mm2)	435	437	436	400-550

2.1.3. Steel reinforcement bars

Each concrete slab was reinforced with two layers of steel bars in both directions with (diameter 10 mm at spacing 100 mm center to center) as shown in Fig.2. The test results and the considered standard of the steel reinforcement specimen are shown in Table 3.

Fig.2 Steel Reinforcement of Concrete Slab of Composite Beam

Table 3 Tensile test results of steel reinforcement specimen

Bar Diameter (mm)	∅10	ASTM A 615/A 615M Requirement
Yield Stress (N/mm^2)	485	420 Min
Ultimate Strength (N/mm^2)	690	620 Min
Elongation (%)	13	9 Min

2.1.4. Stud shear connectors

The dimensions of stud shear connectors which used (75 mm height and 16 mm diameter). The stud shear connectors were joined to the top of a steel I-section by welding to oppose longitudinal slip and vertical detachment between the concrete slab and the steel beam as shown in Fig.1 and 2. The results and the considered standard for tested stud shear connectors are shown in Table 4.

Table 4 Tensile test results of stud shear connector

Stud Diameter (mm)	16	ASTM A 307 Requirement
Yield Stress (N/mm^2)	370	250 Min
Ultimate Strength (N/mm^2)	440	414 Min

2.2 Degrees of shear connection DSC of composite beams

The distance between welded studs were decided according to the plastic analysis and design method that adopted by Eurocode 4 of the composite beam section with full shear interaction. The location of the plastic neutral axis PNA has three cases, as shown in Fig.3.

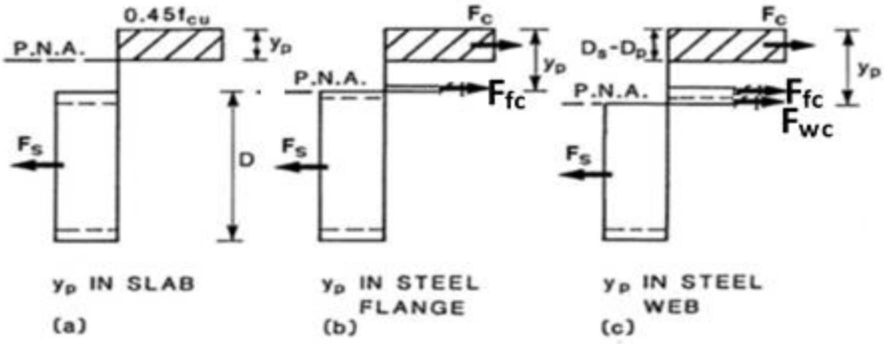

Fig. 3 The possible location of the plastic neutral axis PNA (Eurocode 4)

For the present case, the location of PNA is in concrete slab, case (a), the compression and tensile forces of the composite beam section are:

$F_C = 0.45\ f_{cu}\ B_e\ y_p$ Eq. 1

$F_s = f_y\ A_e$ Eq. 2

And the distance y_p can be found by:

$y_p = f_y . A/(0.45\ f_{cu}\ B_e)$ Eq. 3

Where: f_y: yield stress of steel section (260 Mpa Table 2), A_e: steel section area (1610mm^2), f_{cu}: cube compressive strength of concrete slab (24 Mpa Table 1) and B_e: the effective breadth of the slab (400 mm).

From Eq.3, the distance y_p=96.9 mm, therefore the assumption of location of PNA is correct.

The shear force should be transmitted the smaller of Fc and Fs to transfer the shear in the zones between zero and maximum moment. Therefore, the number of shear connectors required for half member is:

$N_p = \frac{\min(F_c,F_s)}{P_R}$ Eq. 4

Where, P_R is the force in each shear connector, and

$P_R = 0.6\ P_Q$ Eq. 5

Where, P_Q is the characteristic resistance of the stud and given by

$P_Q = 0.8\ f_u \frac{\pi d^2}{4}$ Eq. 6

Where, f_u is the ultimate tensile strength of the stud steel (440 Mpa Table 4) and d is the stud diameter (16 mm Table 4).

From above equations P_Q=70738 N, P_R=42443 N, min(F_C,F_S)=418600 N and Np=10

Then, the spacing along the full length can be found by

$S = \frac{L}{2N_p - 1}$ Eq.7

The spacing along composite specimen beam S (120 mm from Eq. 7) will provide full shear interaction between concrete slab and I-section steel beam.

For partial composite beams, the compressive force in the slab F_C is limited as a function of the steel-concrete connection capacity, and the relative slip between steel and concrete which leads to reduce the section capacity. By decreasing the section capacity in Eq. 4 with target degrees of connections to get the corresponding stud distance for each degree of connection from Eq. 7, the results are shown in Table 5.

Table 5 Distance of Shear Studs and Degrees of Connection of Tested Beams

NC Beams	LC Beams	Studs distance (mm)	Degrees of shear connection
NC040	LC040	325	40%
NC060	LC060	205	60%
NC080	LC080	150	80%
NC100	LC100	120	100%

2.3. Instrumentation and testing procedure

The details of the tested composite beam specimens are shown in Fig.1. By using universal testing machine (TORSEE) 200 tons capacity, a monotonic load was applied at the mid-span of 2.3m effective span simply supported composite beams as shown in Fig.4. The applied loads were increased successively up to failure of testing beams. The measurements were recorded at the end of each load increment for the mid-span deflection by using a laser dial gauge of 0.01mm precision and relative end slip by using a dial gauge of 0.01mm precision. Also, the crack development were recorded by observation.

Fig.4 Steel Concrete Composite Beam Specimen under Test

3. Results and discussion

3.1. Experimental results

3.1.1. Concrete

Table 6 shows the test results of compressive strength, slump, and density of concrete that used to cast the slabs of the tested composite beams. Also, Fig.5 shows the reduction in concrete slab weight by using lightweight concrete instead of normal concrete, which about 27%.

Table 6 Properties concrete slabs of composite beams

Concrete Slab	Composite Beam	Slump mm	Concrete Density Kg/m^3	Average of 3 cubes f_{cu} (MPa) at 7 days	Average of 3 cubes f_{cu} (MPa) at 28 days	Average f_{cu} (MPa) at 28 days
Normal weight	NC040	125	2315	18.3	24.5	24.7
	NC060	125	2312	18.6	24.9	
	NC080	126	2315	18.2	24.5	
	NC100	125	2315	18.4	24.7	
Light weight	LC040	125	1685	18.9	24.3	24.4
	LC060	125	1688	19.3	24.6	
	LC080	126	1687	19.3	24.5	
	LC100	126	1685	19.1	24.3	

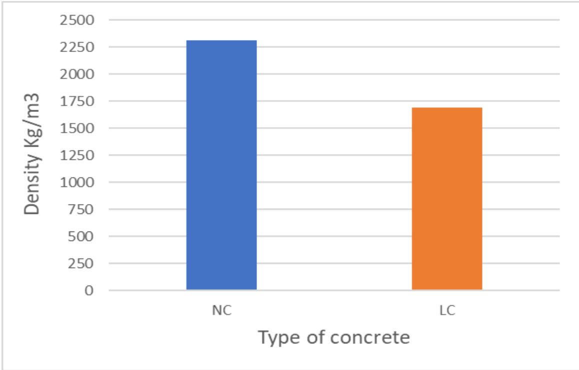

Fig.5 The reduction in concrete slab weight

3.1.2. Failure modes

Flexural failure modes were observed from the tests of all specimens. The crack patterns were flexural cracks at the mid span of the tested specimens and a shear flexural cracks out of the mid span region. The flexural failure modes started by yielding the steel beam and then crushing of the concrete flange in the mid span of the tested beams. The essential differences between the specimens with normal and lightweight concrete were the intensity and start of cracks. The intensity of cracks in NC was more than LC as shown in Fig.6, but the stage loading of appearing cracks in LC was earlier than NC which have same DSC. Table 7 shows the loading stages for first crack observation and accelerating of cracks development. There was no separation appeared between the concrete slab and steel beam for all the tested specimens.

Failure Modes and crack pattern for testing specimens

Table 7 loading stages for first crack and cracks development

Type of slab concrete	Composite Beam	FCLS[1] %	LSIC[2] %
Normal weight	NC040	38	68
	NC060	48	75
	NC080	67	83
	NC100	76	93
Light Weight	LC040	24	51
	LC060	31	63
	LC080	54	74
	LC100	70	86

1 Load of first crack dividing by ultimate load.
2 Load stage of increase intensity of cracks dividing by ultimate load.

3.1.3. Load deflection response

The experimental results for tests of eight specimens of composite beams are shown in Table 8. The applied load mid-span deflection relationships for the tested NC and LC specimens are shown in Figs. 7 and 8, respectively. For both NC and LC specimens, the load deflection curves can be divided into linear and nonlinear parts. The first part is represented by the linear elastic response of the tested specimens. For NC, the elastic range was continued until the load reached about (40%, 50%, 70% and 80%) of the ultimate load for DSC (40%, 60%, 80% and 100%) respectively, whereas for LC specimens was about (25%, 35%, 60% and 70%) of the ultimate load for DSC (40%, 60%, 80% and 100%) respectively. It was found that the stiffness, which represents the slope of the linear part of the curves, proportional with the DSC for NC and LC, as shown in Fig. 9. Also, the maximum deflection of NC is greater than LC specimens of same DSC, but should be noted that the deflections of LC are greater than NC at same applied loads, as shown in Figs.10, 11, 12 and 13. The second part represents the nonlinear response of the tested specimens when the applied load exceeds the yield load in the specimens, where the stiffness gradually degraded until the failure occurred. It was noted that the nonlinear stage becomes more obvious with decrease the DSC for all specimens and especially for LC specimens, therefore, the cracks were appearing in early loads in the concrete slabs as shown in Table 7.

Table 8 Experimental results for test specimens of composite beams

Beam No.	NC40	NC60	NC80	NC100	LC40	LC60	LC80	LC100
Ultimate Load (kN)	105.0	112.8	121.6	129.5	94.2	99.1	108.4	117.7
Max. Deflection (mm)	28.1	25.4	21.5	16.7	25.5	22.1	18.2	15.7
Service Load (kN)[1]	70.0	75.2	81.1	86.3	62.8	66.1	72.3	78.5
Deflection at Service Load (mm)	8.3	8.1	5.7	5.3	10.4	8.8	6.9	5.8
Beam Stiffness (kN/mm)[2]	8.43	9.28	14.22	16.29	6.04	7.51	10.47	13.53
End Slip (mm)	3.13	2.81	2.32	1.74	8.43	6.52	5.42	2.5
Ultimate Moment Capacity (kN.m)	60.38	64.86	69.92	74.46	54.17	56.98	62.33	67.68

1 the service load is represented as two third of ultimate load [Abbas A. M].
2 beam stiffness is evaluated by dividing the service load on the corresponding deflection [Resan S. F.].

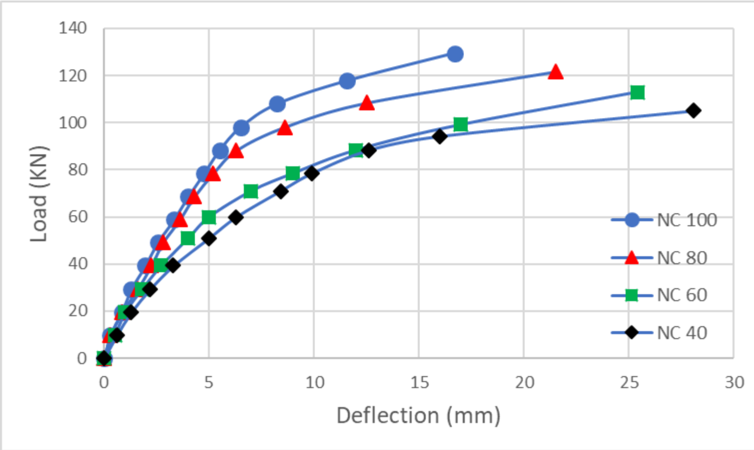

Fig.7 Applied load – midspan deflection relationships for testing NC beams

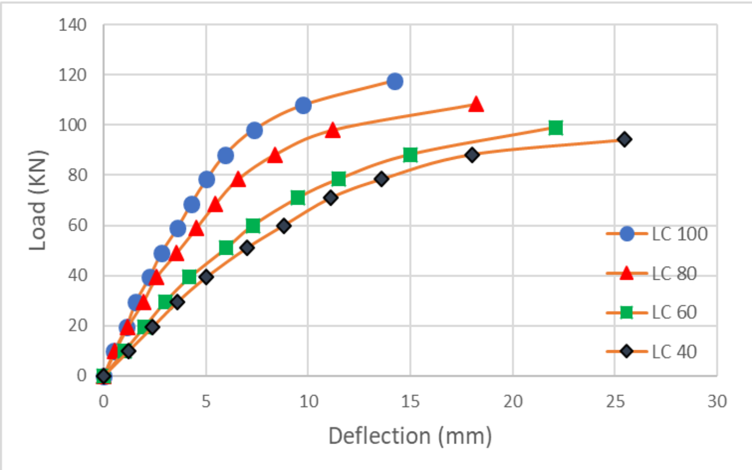

Fig.8 Applied load – midspan deflection relationships for testing LC beams

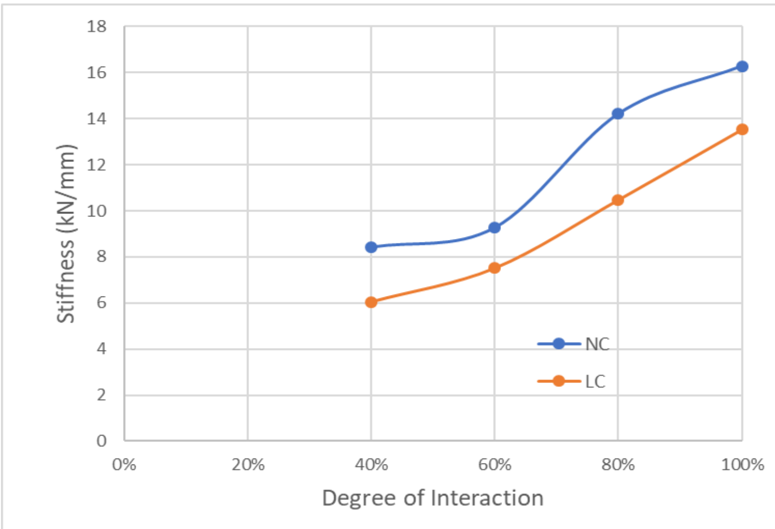

Fig.9 Stiffness – degree of connection relationships for testing beams

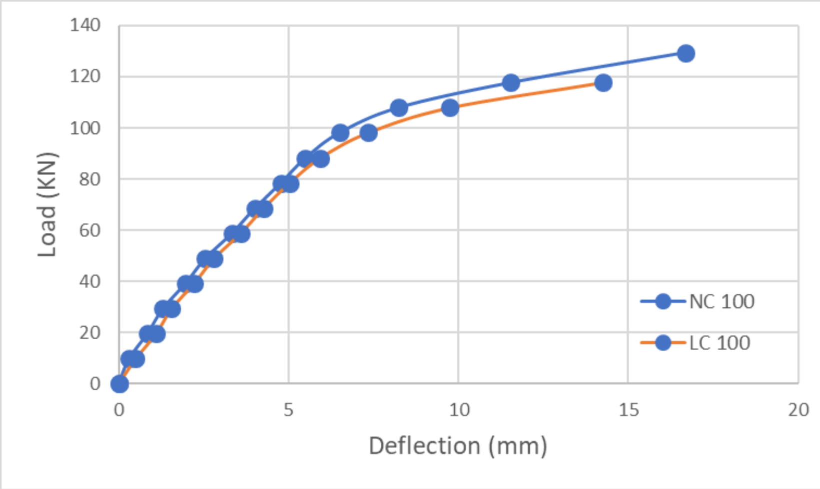

Fig.10 Behavior comparison between NC and LC tested beams with 100% DSC

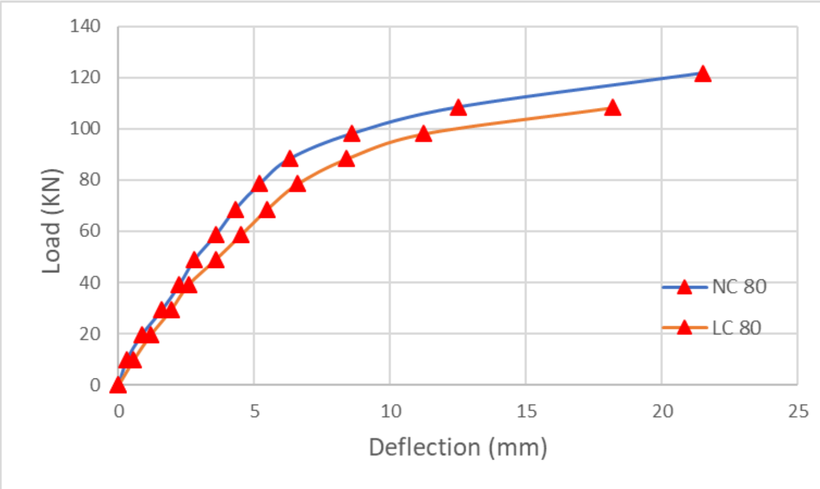

Fig.11 Behavior comparison between NC and LC tested beams with 80% DSC

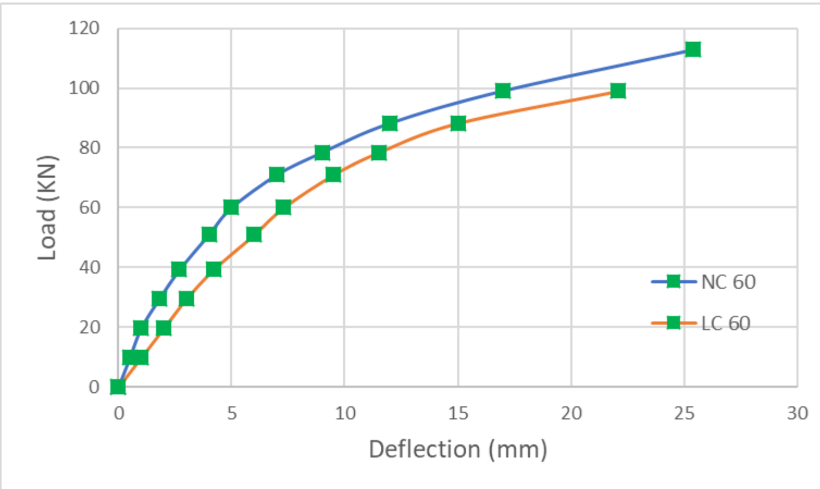

Fig.12 Behavior comparison between NC and LC tested beams with 60% DSC

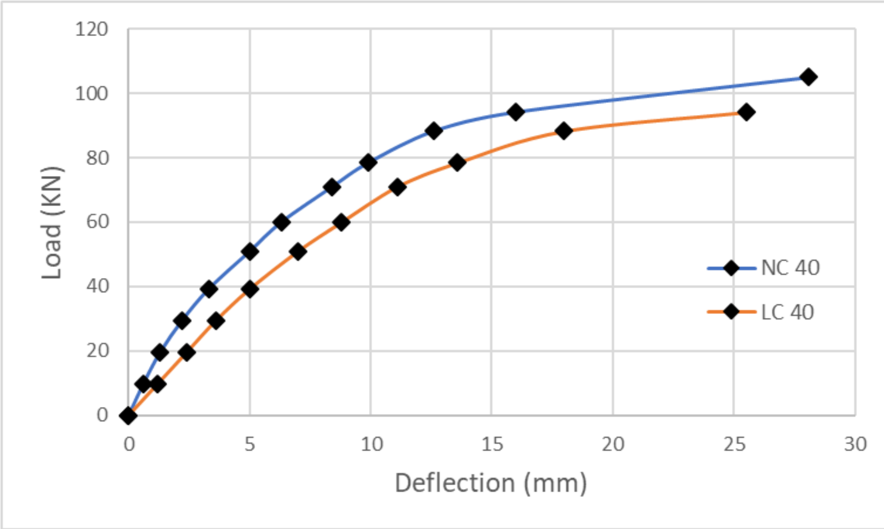

Fig.13 Behavior comparison between NC and LC tested beams with 40% DSC

3.1.4. Ultimate strength

The experimental result show that the ultimate strength of LC specimens was less than NC specimens which have same DSC. The decrease ratio was approximately constant, which is about (10.6%). Also, the ultimate strength of both types of specimens was increased with the increase in DSC, as shown in Fig.14.

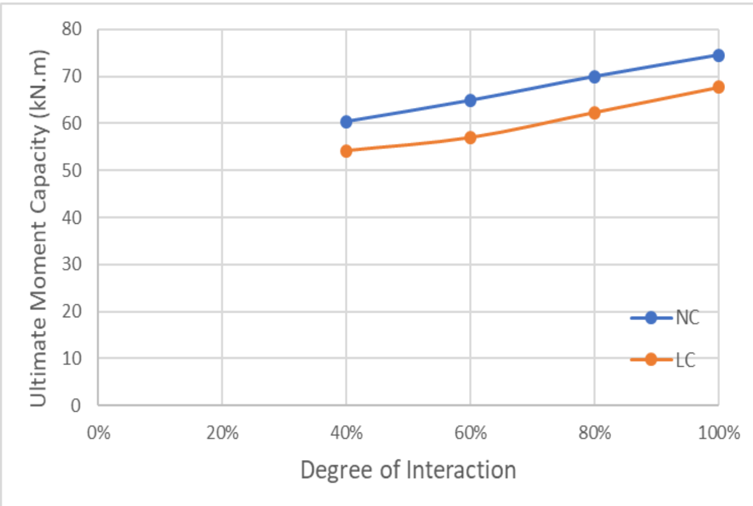

Fig.14 Variation of ultimate moment capacity with DSC for NC and LC beams

3.1.5. Relative end slip

The experimental results showed that the relative end slip [Johnson R. P.] between the steel beam and the concrete slab, for the NC and LC specimens was decreased with the increase of DSC, as shown in Figs.15 and 16, respectively. Also, the end slip for LC specimens was greater than that for NC specimens, which have the same DSC, as shown in Figs.17, 18, 19 and 20. The relative end slip that corresponding to the ultimate load for all tested specimens are shown in Table 8.

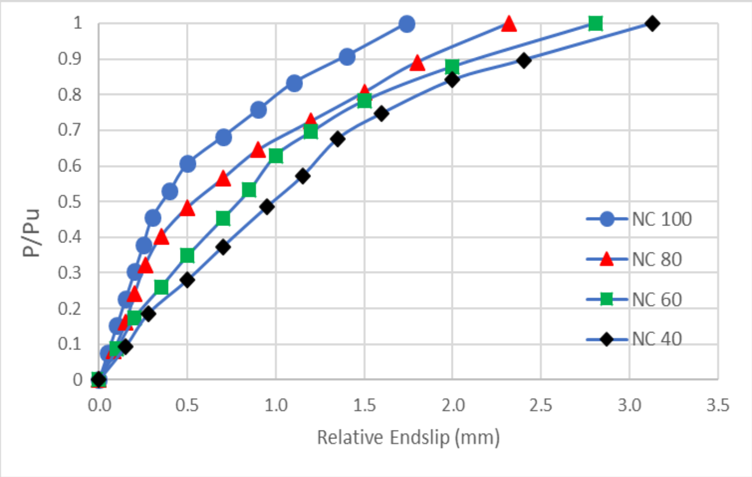

Fig.15 Variation of relative end slip with applied load for NC beams

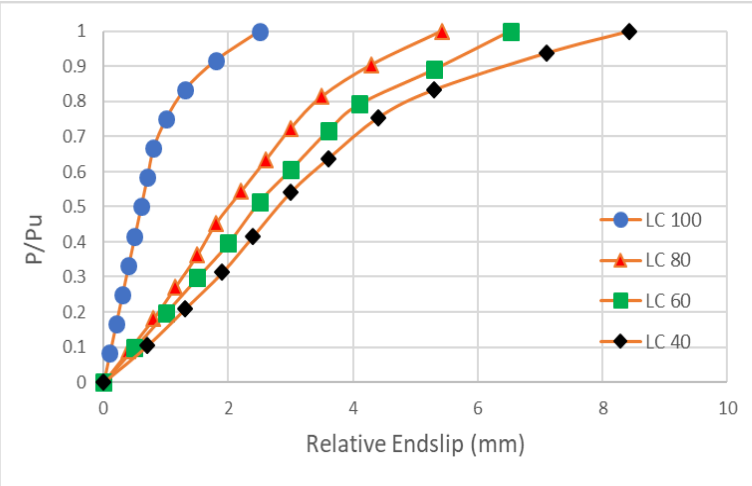

Fig.16 Variation of relative end slip with applied load for LC beams

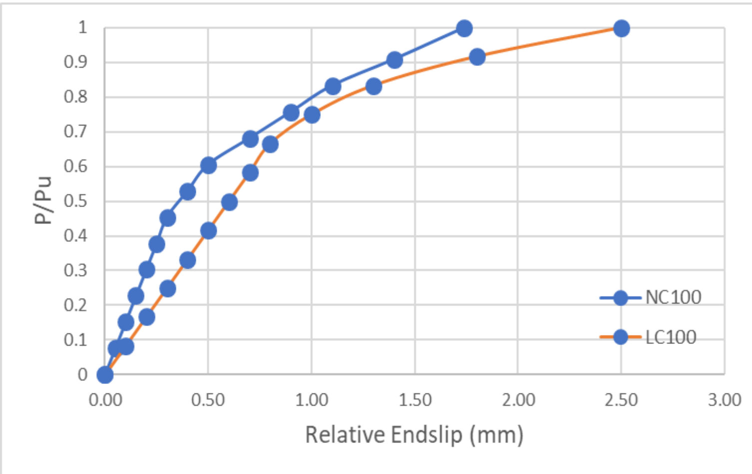

Fig.17 End slip comparison between NC and LC tested beams with 100% DSC

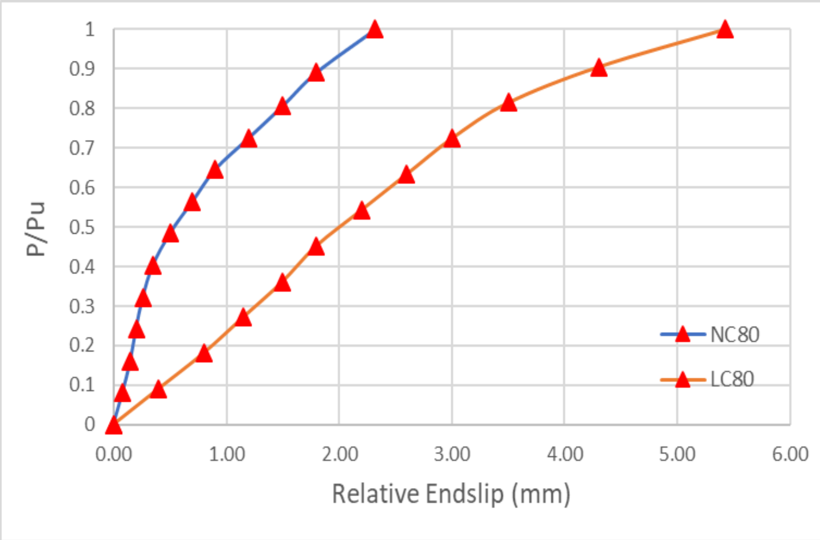

Fig.18 End slip comparison between NC and LC tested beams with 80% DSC

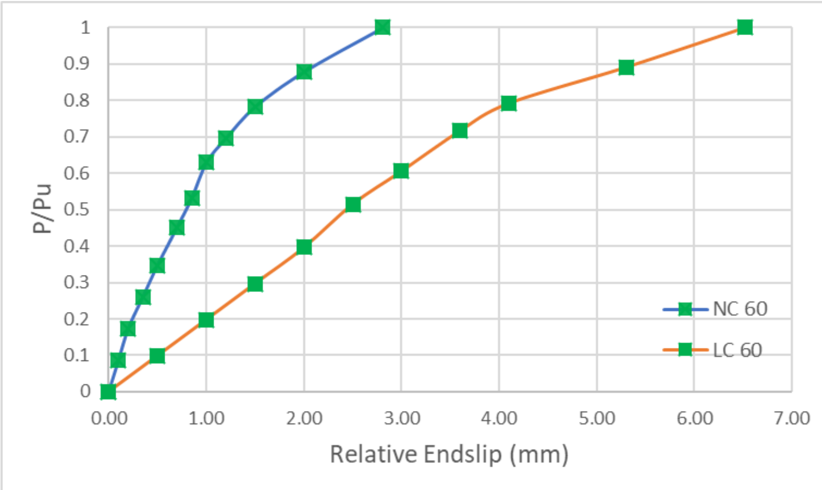

Fig.19 End slip comparison between NC and LC tested beams with 60% DSC

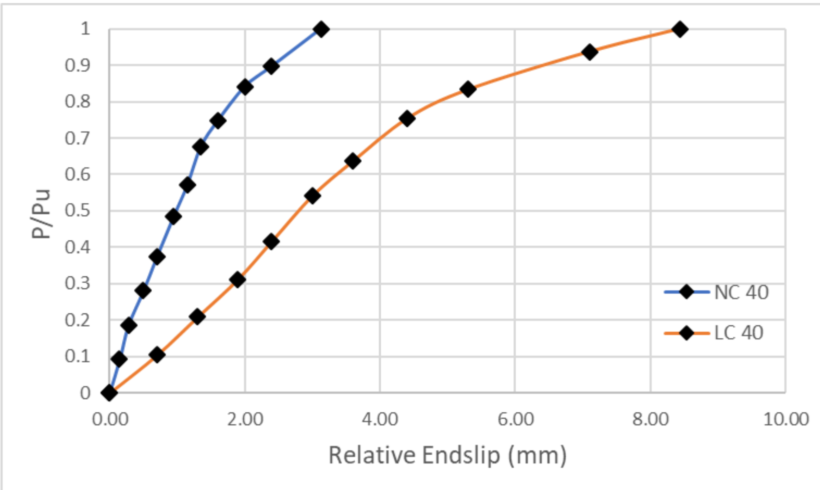

Fig.19 End slip comparison between NC and LC tested beams with 40% DSC

3.2. Analytical analysis

3.2.1. Moment capacity

The force resisted by the connectors Fcs are taken as their total capacity (Fcs < Fc) between points of zero and maximum moment and by assuming all connectors have same resistance to shear P_R, therefore the depth of compressive stress block in slab is,

$x_p = F_{cs}/(0.45\, f_{cu}\, B_e) < h_c$ [Eurocode 4]

For Full shear connection, the moment capacity M_f can be found by:

$$M_f = F_{cs}\,\frac{x_p}{2}$$

For partial shear connections, the relative slip between steel and concrete leads to two neutral axes: one on the concrete slab and the other in the steel beam. The moment of resistance for partial shear connections beam Mp can be found out using stress block shown in Fig.21 therefore,

$M_P = F_{sp}\left(h_g + h_c - \frac{x_p}{2}\right) - F_{cf}\,\frac{x_a+h_c-x_p}{2}$ for x_a at flange of steel section

$M_P = F_{sp}\left(h_g + h_c\right) - F_{cs}\,\frac{x_p}{2} - 2F_{cf}\left(h_c + \frac{t_f}{2}\right) - F_{cw}\,\frac{x_a+h_c-t_f}{2}$ for x_a at web of steel section

Where, $F_{cf} = b_f t_f f_y$ and $F_{cw} = F_{sp} - F_{cs} - 2F_{cf}$

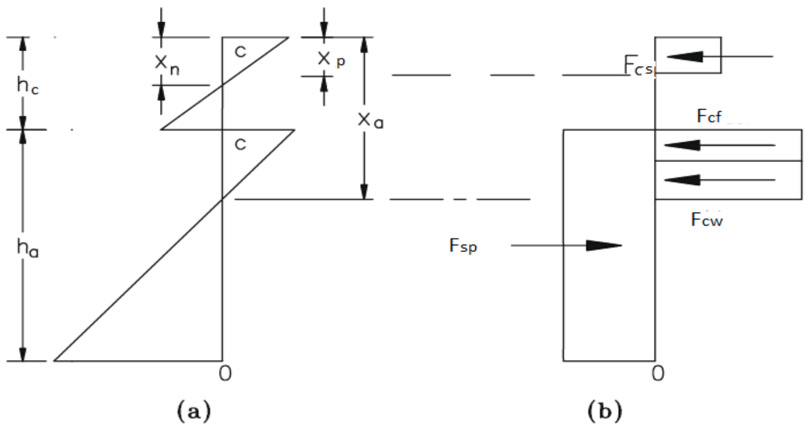

Fig.21 Stress block for partial shear connection of composite beam[Eurocode 4]

3.2.2. Deflection

The analysis is done in terms of equivalent steel section. the concrete area is converted into equivalent steel area by applying modular ratio m = (Es/Ec).

Where,

$E_c = w^{1.5} 0.043\sqrt{f_c'}$ [ACI 318M-14]

Es = 200000 MPa [ASTM A 36/A 36M – 04]

f_c' is compressive strength of cylinder = 0.8 f_{cu} and w is the density of concrete.

Then determine the transformed moment of inertia, I_{TR} to find I_{eff} by

$I_{eff} = I_s + \sqrt{\frac{F_{cs}}{\min(F_c, F_s)}}\,(I_{TR} - I_s)$ [Maximiliano Malite]

Finally, the maximum deflection for midspan load can be found by

$\Delta = P\,L^3/(48\ Es\ I_{eff})$

4. Comparison of analytical predictions with test results

As shown above the analytical analysis of the moment capacity of composite section depend on f_{cu} for the concrete, where both types of NC and LC had same compressive strength, therefore the analytical results of moment capacity will be same for each DSC. On the other hand, the analytical analysis of deflection considers this difference in concrete types by Ec equation. Table 9 shows the comparison between experimental and analytical results. The comparison of results shows a good agreement with NC fully composite beam only. Also, the results shown that, the imprecision is proportional with DSC.

Table 9 Comparison between experimental and analytical results for composite beams

Beam No.	Pu (kN) Anal.	Mu (kN.m) Anal.	Max. Δ (mm) Anal.	Pu (kN) Exp.	Mu (kN.m) Exp.	Max. Δ (mm) Exp.	Mu Anal./Exp.	Δ Anal./Exp.
NC40	124.7	73.70	37.2	105.0	60.38	28.1	1.22	1.32
NC60	134.1	77.01	32.2	112.8	64.86	25.4	1.19	1.27
NC80	137.9	79.32	25.8	121.6	69.92	21.5	1.13	1.20
NC100	140.2	80.62	17.7	129.5	74.46	16.7	1.08	1.06
LC40	124.7	73.70	40.6	94.2	54.17	25.5	1.36	1.59
LC60	134.1	77.01	33.9	99.1	56.98	22.1	1.35	1.53
LC80	137.9	79.32	27.1	108.4	62.33	18.2	1.27	1.49
LC100	140.2	80.62	19.3	117.7	67.68	15.7	1.19	1.23

5. Conclusions

- The initial stiffness of the beams was decreased about 20% by changing the concrete slab from normal to lightweight.
- In spite of the maximum deflection of NC greater than LC specimens, but the defection of LC at same load increment is greater than NC specimens.
- The ultimate strength of the steel concrete composite beams was decreased about 10.6 % by changing the concrete slab from normal to light for the same compressive strength.
- The measured end slip for beams with LC had bigger values for different degrees of shear connection compared with values obtained from the tests of beams with NC.
- The analytical analysis for NC fully shear connection shown a good agreement with experimental results and the other results were overestimated.

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