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Experimental Investigating the Strain of The Steel-concrete Composite Beams with Different Shear Connection Degree

Nghiên cứu thực nghiệm biến dạng của dầm liên hợp thép - bê tông với mức độ liên kết khác nhau

> **VAN PHUOC NHAN LE[1*], THAI HOA DINH[2]**
[1*]Ho Chi Minh City University of Technology, Vietnam National University of Ho Chi Minh City
Email: lvpnhan@hcmut.edu.vn
[2]Center for Development of Building Technologies in West Region (IBST)
Email: thaihoa1985.ibst@gmail.com

ABSTRACT

Shear connectors play an important role in steel-concrete composite beams and affect the bending behaviors of the steel-concrete composite beams, such as the load capacity, the vertical deflection, the relative slip between the steel girder and the concrete slab, and so on. Many kinds of shear connectors have been used in construction and the most popular shear connector used in the world is the stud shear connector. However, perfobond shear connectors have been more and more used. In this study, perfobond shear connectors were welded on the top flange of the steel girder and along the beam length to prevent the relative slip between the steel girder and the concrete slab of steel-concrete composite beams. A test program was carried out on two large-scale steel-concrete composite beams to investigate the effect of the shear connection degree on the strain of the steel-concrete composite beams. Two steel-concrete composite beams had different numbers of shear connectors, one of them had twenty shear connectors and the other had ten shear connectors.

Keywords: Perfobond shear connector, shear connection degree, steel-concrete composite beam, strain.

TÓM TẮT

Liên kết kháng cắt đóng một vai trò quan trọng trong dầm liên hợp thép - bê tông và ảnh hưởng đến ứng xử uốn của dầm liên hợp thép - bê tông. Như khả năng chịu tải, độ võng, biến dạng trượt tương đối giữa dầm thép và bản bê tông,... Nhiều loại liên kết kháng cắt đã và đang được sử dụng trong xây dựng trong đó phổ biến nhất là liên kết kháng cắt dạng chốt. Tuy nhiên, liên kết kháng cắt dạng perfond hiện ngày càng được sử dụng rộng rãi. Trong nghiên cứu này, liên kết kháng cắt dạng perfobond được hàn vào cánh trên của dầm thép, dọc theo chiều dài dầm để ngăn cản sự trượt tương đối giữa dầm thép và bản bê tông của dầm liên hợp. Quá trình thí nghiệm được tiến hành trên hai dầm có kích thước thực để nghiên cứu ảnh hưởng của mức độ liên kết kháng cắt đến biến dạng của dầm liên hợp thép - bê tông. Hai dầm liên hợp thép - bê tông có số liên kết kháng cắt khác nhau, một trong hai dầm có hai mươi liên kết kháng cắt, dầm còn lại được bố trí mười liên kết kháng cắt.

Từ khóa: Liên kết kháng cắt dạng perfobond; mức độ liên kết kháng cắt; dầm liên hợp thép - bê tông, biến dạng

1. INTRODUCTION

Perfobond shear connectors have been widely studied around the world. Many researchers carried out push-out tests with small specimens to investigate the mechanical behavior of the shear connectors by changing the parameters of perfobond shear connectors such as the concrete compressive strength, the thickness of perfobond, and the dimensions of perfobond holes. These puh-out tests determined the load capacity of the shear connectors, the relative slip between the concrete slab and steel girder, and the failure modes of specimens by changing the parameters. From these results, researchers can choose suitable perfobond shear connectors to use for the steel-concrete composite beams [1, 2, 3, 4, 5, 6, 7, 8, 9 10]. To investigate the bending behavior of the steel-concrete composite beam, large-scale beams have usually been used to test. The bending behavior observed often is the load capacity, the vertical deflection, and the relative slip between the concrete slab and steel girder of the steel-concrete composite beams. E.G. Oguejiofor and M.U. Hosain tested six full-size composite beam specimens with perfobond rib shear connectors embedded in the solid concrete slab. The purpose of this study is to investigate the effectiveness of more perfobond rib connectors of shorter length and the effectiveness of more perfobond rib connectors of shorter lengths [11]. Brian Uy studied the effects of partial shear connection for beams and joints subjected to hogging moments [12]. Many full-scale steel-concrete composite beams using stud and other shear connections were tested. Yong Yuan executed experiments on composite beams with high-strength steel and concrete to investigate the effect of high-strength engineering materials on the overall flexural response, including failure modes, load-deflection behavior, strain response and interface slip [13]. Lotla Sandeep Reddy studied the behavior of steel-concrete composite beams with different spacing of shear connectors subjected to pure bending [14]. Sylvester O. Osuji carried out four full-scale steel-composite beams to investigate the behavior of steel-concrete composite beams under negative bending considering the load-deflection, shear connection, and concrete-steel interface slip characteristics [15]. Y. Liu studied five steel-concrete composite beams with U-shaped steel girders and different angle connector intervals and installation locations to investigate the flexural behavior of steel-concrete composite beams [16]. Hayder Talib Nimnim observed the effect of openings in the concrete slab of the composite beams on the bending behavior of the steel-concrete composite beams [17]. Taniguchi carried out four composite beams with expansion joints to investigate the mechanical performance of the steel-concrete composite beams [18]. Zhi Huang carried out four steel–concrete composite box girders with different shear connection degrees and ratios of web height to thickness to study the seismic behavior of a steel-concrete composite box girder, such as the hysteresis law, skeleton curve, and stiffness degradation law [19]. In this study, the experimental program was performed on two full-scale steel-concrete composite beams to investigate the effect of the shear connection degree on the strain of the steel-concrete composite beams. Perfobond shear connectors were used in these steel-concrete composite beams.

2. TEST PROGRAM

2.1 Materials

2.1.1 Concrete

Concrete used in steel-concrete composite beams was M350. A group of six-cylinder concrete samples was tested to determine the compressive strength of concrete at the same time as the bending test. The aggregate gradation of the concrete is presented in Table 1. The concrete was cured in 28 days and tested in compliance with TCVN 3118-1993 [15]. The concrete compressive strength test was carried out at the same time as the bending test. The test results of concrete compressive strength are displayed in Table 2.

Table 1. The aggregate gradation for 1 m^3 concrete

Material component	Unit	Quantity
Holcim cement PCB40 PowerS	kg	330
Bank sand	kg	495
Crushed sand	kg	335
Stone	kg	1115
Water	littre	165
Addition agent BASF Sky 8735	kg	3.3

Table 2. Mechanical characteristics of concrete

Specimen	Dimensions (mm)	Failure load (kN)	Compressive strength (MPa)
M1	150×150×150	769.5	34.2
M2	150×150×150	866.3	38.5
M3	150×150×150	843.8	37.5
M4	150×150×150	855.0	38.0
M5	150×150×150	823.5	36.6
M6	150×150×150	792.0	35.2
Average value		824.9	36.7

2.1.2 Plate, hot-rolled steel, and reinforcement

The plate and round steel used in the steel-concrete composite beams had the same characteristics as specimens in the push-out test. The plate steel was used to create perfobond shear connectors. In this experiment, the steel of the girder was tested according to ASTM 370-14 [100]. Three specimens of steel M1-1, M1-2, and M1-3 were tested to determine the mechanical charactreristics the steel. The stress-strain relation curves of these specimens are shown in Figure 1, and the test result of steel is presented in Table 3.

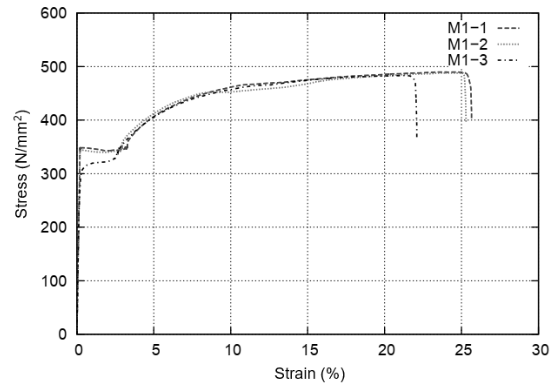


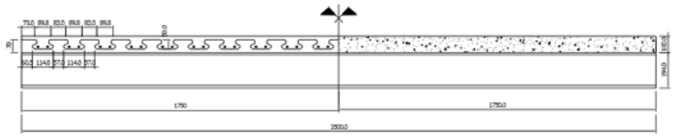
Fig 1. The relationship cuvers of stress-strain of steel

Table 3. The test result of the steel

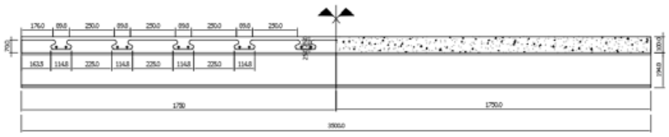
Specimen	Reinf. steel	Plate steel	Hot-rolled steel
Yield strength f_y (MPa)	347	320	284
Ultimate strength f_u (MPa)	488	425	389
Elastic modulus E (MPa)		200×10³	200×10³

2.2 Specimens

The steel-concrete composite beams consisted of the steel girder, the concrete slab, perfobond shear connectors, the transverse reinforcements passing through the connector holes, and a mesh of reinforcements in the concrete slab. Perfobond shear connectors were welded on the top flange of the steel girder and along the beam length. The perfobond shear connectors prevented the relative slip between the steel girder and the concrete slab. The steel girder was a hot-rolled steel of I-194×150×6×9. The perfobond shear connectors had a thickness of 8 mm and a shape Ʊ with an area of 4490 mm^2. The number of perfobond shear connectors in beams was different to evaluate the effect of shear connection degree on the strain of the steel-concrete composite beams. The number of perfobond shear connectors of beam 1 and beam 2 was twenty and ten shear connectors, respectively, as shown in Figure 2. The length of the beams was 3500 mm, and the supports were 100 mm from the beam ends. The test model was four bending point beams, as shown in Figure 3. The load cell with a load level of 2000 kN was used to increase the load for the bending test. The load was transferred through a steel beam. Linear Variable Displacement Transducers (LVDT) 1, 2, and 3 were used to measure vertical deflection along the length of the steel-concrete composite beams. LVDT 4, 5, 6, and 7 were used to measure the relative slip between the concrete slab and the steel girder. Strain gauges G1, 2, 3, 4, and 5 were attached to the steel girder to measure the strain of the steel girder, and strain gauges G6 and 7 were used to measure the strain of concrete at the top and bottom surfaces of the concrete slab. Strain gauges G8, 9, 10, 11, and 12 were placed at perfobond to measure the strain of the perfobond shear connectors during loading, and a four-point bending model was used to observe the bending behavior of the steel-concrete composite beams, as shown in Fig. 3. The section of the steel-concrete composite beam is shown in Figure 4.



a. Beam 1 with 20 perfobond shear connectors



b. Beam 1 with 10 perfobond shear connectors

Fig 2. The steel-concrete composite beams

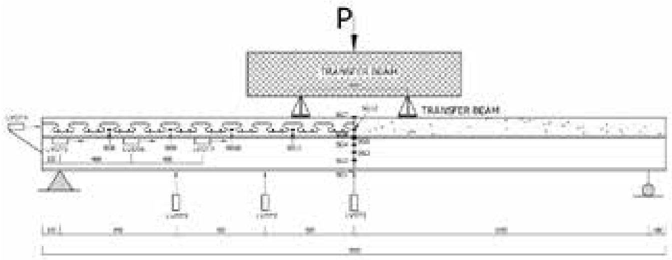


Fig. 3 Test model

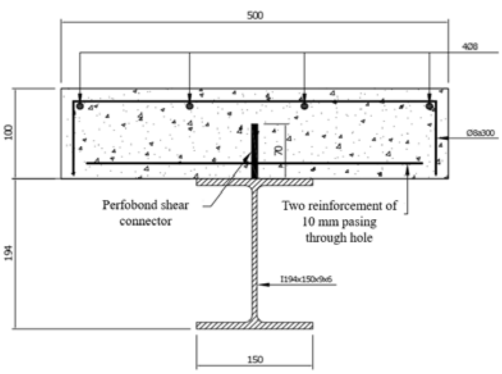


Fig 4. Section of the steel-concrete composite beam

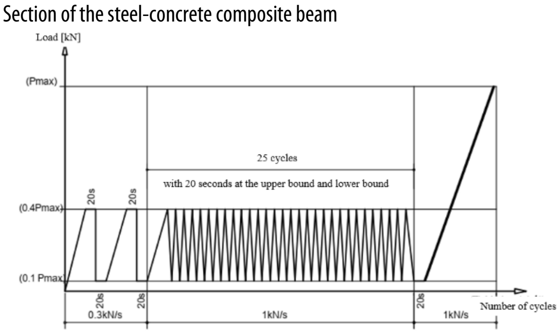


Fig 5. The incremental loading

2.3 The shear connection degree

The shear capacity of one shear connector was obtained from a push-out test of 141.42 kN

Determining the shear connection degree for beam 1 and beam 2.

The plastic axial resistance of the steel girder (class 1):

$N_{pla} = A_a f_y/\gamma_a = [(19.4 - 2\times0.9)\times0.6 + 2\times15\times0.9]\times28.4/1.0 = 1066.70$ kN

The plastic axial resistance of the concrete slab:

$N_{cf} = b_{eff} h_c 0.85 f_{ck}/\gamma_c = 50\times10\times0.85\times3.67/1.0 = 1559.75$ kN

Note: $\gamma_a = 1.0$ Partial safety factor of steel

$\gamma_c = 1.0$ Partial safety factor of concrete

$V_{IN} = \min(N_{pla}; N_{cf}) = 1066.70$ kN

The number of necessary shear connectors for half beam:

$N_f \geq V_{IN}/P_{Rd} = 1066.70/141.42 = 7.54$ (shear connectors/half-length).

Therefore, beam 1 with 20-shear connectors was considered a full-shear connection beam, and beam 2 with 10-shear connectors was considered a partial-shear connection beam (66.67%).

2.3 Test setup

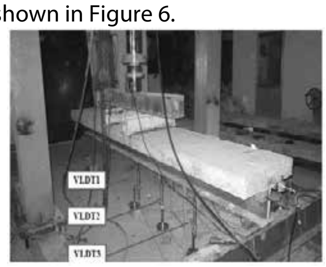
Figure 5 illustrates the incremental loading process. The applied load was divided into three phrases:

Phase 1: Increasing load from 0 to 40% predicted failure load (P_{max}), and then repeating 2 times.

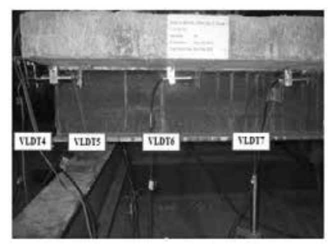
Phase 2: Increasing load from 10% P_{max} to 40% P_{max}, and then repeat 25 times. This stage is to eliminate the adhesive force, friction, and residual strain of testing.

Phase 3: After ending phase 2, increase load from 10% P_{max} to failure load, continue increasing load until the load remains 90% P_{max}, and stop testing.

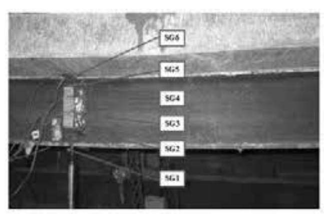
The load cell with a load level of 2000 kN was used for the bending test. The load was transferred through a steel beam. Linear Variable Displacement Transducers (LVDT) 1, 2, and 3 were used to measure vertical deflection along steel girder length, as shown in Figure 6. LVDT 4, 5, 6, and 7 were used to measure the relative slip between the concrete slab and the steel girder. Strain gauges were used to measure the strain of the concrete slab and the steel girder during loading. Some practical images of the test program are shown in Figure 6.



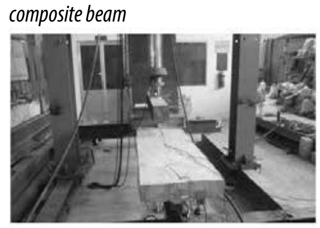
a. Placing LVDT 1, 2, and 3 for measuring the vertical deflection of steel-concrete composite beam



b. Placing LVDT 4, 5, 6, and 7 for measuring the relative slip between the steel girder and the concrete slab of the steel-concrete composite beam



c. Attaching strain gauges 1, 2, 3, 4, 5, and 6 for measuring the strain of the steel girder and concrete slab



d. Testing model

Fig 6. The real images of the test program

3. TEST RESULTS AND ANALYSIS

3.1 Strain of the steel-concrete composite beam

The failure load of Beam 1 and Beam 2 are 242.22 kN and 225.85 kN, respectively. The strain of Beam 1 and Beam 2 at some load levels are presented in Table 4 and Table 5. The strain of the steel-concrete composite beam was measured at locations along the section height, as shown in Figure 7 (Beam 1) and Figure 8 (Beam 2). The maximum compressive strain occurred on the top surface of the concrete slab and the maximum tension strain on the steel girder's bottom surface. The test results showed that the strain in the steel-concrete composite beams significantly changed when the load level reached 80%P_{max}. Before reaching this load level, the strain of the beam was rather small in comparison with the strain at the maximum stress for the concrete or the strain at the yield strength of steel (2‰). After 80%P_{max}, the strain in beams gradually increased. At the failure load, the strain at the outer fibers of the steel girder strongly increased.

Table 4. Strain of Beam 1 at location from section bottom (‰)

Load level	SG1	SG2	SG3	SG4	SG5	SG6	SG7
0% $P_{1,max}$	0.00	0.00	0.00	0.00	0.00	0.00	0.00
20% $P_{1,max}$	0.36	0.28	0.20	0.11	0.03	0.02	-0.17
40% $P_{1,max}$	0.74	0.58	0.40	0.24	0.06	0.03	-0.35
50% $P_{1,max}$	0.85	0.79	0.53	0.31	0.08	0.03	-0.45
60% $P_{1,max}$	1.39	1.17	0.80	0.48	0.13	0.08	-0.60
80% $P_{1,max}$	2.65	2.24	1.86	1.29	0.41	0.37	-1.12
100% $P_{1,max}$	9.67	2.52	2.45	1.92	1.26	1.96	-2.37

Table 5. Strain of Beam 2 at location from section bottom (‰)

Load level	SG1	SG2	SG3	SG4	SG5	SG6	SG7
20% $P_{2,max}$	0.33	0.26	0.18	0.10	0.03	0.02	-0.17
40% $P_{2,max}$	0.66	0.53	0.35	0.19	0.06	0.04	-0.35
50% $P_{2,max}$	0.82	0.66	0.44	0.23	0.07	0.04	-0.44
60% $P_{2,max}$	0.99	0.80	0.52	0.28	0.08	0.05	-0.54
80% $P_{2,max}$	1.10	1.38	1.22	0.68	0.20	0.15	-0.97
100% $P_{2,max}$	17.55	9.76	4.39	1.80	0.34	0.16	-3.55

Table 6. Strain of Beam 1 & Beam 2 according to the load levels of Beam 2 (‰)

	Load level	SG1	SG2	SG3	SG4	SG5	SG6	SG7
Beam 1	20% $P_{2,max}$	0.34	0.26	0.18	0.11	0.03	0.01	-0.16
Beam 2	20% $P_{2,max}$	0.33	0.26	0.18	0.10	0.03	0.02	-0.17
Beam 1	40% $P_{2,max}$	0.68	0.54	0.37	0.22	0.06	0.01	-0.32
Beam 2	40% $P_{2,max}$	0.66	0.53	0.35	0.19	0.06	0.04	-0.35
Beam 1	50% $P_{2,max}$	0.85	0.70	0.48	0.28	0.07	0.02	-0.41
Beam 2	50% $P_{2,max}$	0.82	0.66	0.44	0.23	0.07	0.04	-0.44
Beam 1	60% $P_{2,max}$	0.87	0.98	0.66	0.39	0.10	0.03	-0.53
Beam 2	60% $P_{2,max}$	0.99	0.80	0.52	0.28	0.08	0.05	-0.54
Beam 1	80% $P_{2,max}$	2.29	2.00	1.51	1.00	0.30	0.13	-0.95
Beam 2	80% $P_{2,max}$	1.10	1.38	1.22	0.68	0.20	0.15	-0.97
Beam 1	100% $P_{2,max}$	3.50	2.92	2.60	2.37	0.81	0.51	-1.77
Beam 2	100% $P_{2,max}$	17.55	9.76	4.39	1.80	0.34	0.16	-3.55

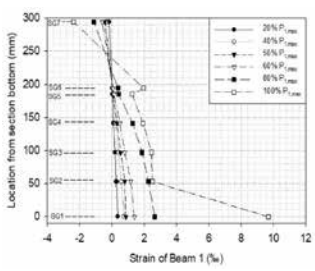


Fig 7. Strain of Beam 1 at mid-span

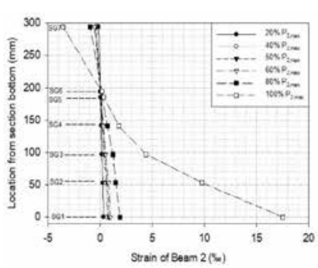


Fig 8. Strain of Beam 2 at mid-span

Table 6 presents the strain of Beam 1 and Beam 2 according to the load levels of Beam 2 to compare the strain in the steel-composite beam with the same load. At the low load levels (under 60%$P_{2,max}$), there is no clear difference in the strain between the two steel-concrete composite beams, as shown in Figure 9 and Figure 10. This can be explained that at the low load, the relative slip between the steel girder and the concrete slab is so small and the effect of the shear connection degree has not been significantly performed. However, at a higher load, the strain in Beam 2 (with a lower shear connection degree) is greater than that of Beam 1 (with a higher shear connection degree), as shown in Figure 11. The increasing load results in overloading the capacity of the shear connectors and the relative slip between the steel girder and the concrete slab. Therefore, the strain in the steel-concrete composite beam with a lower shear connection degree will increase compared to the strain in the steel-concrete composite beam with a higher shear connection degree.

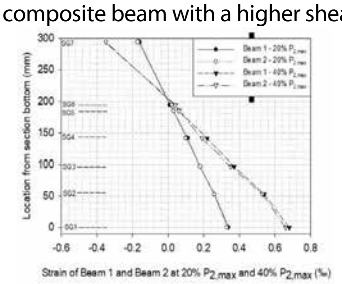


Fig 9. Strain of Beam 1 and 2 at mid-span corresponding 20%$P_{2,max}$ and 40%$P_{2,max}$

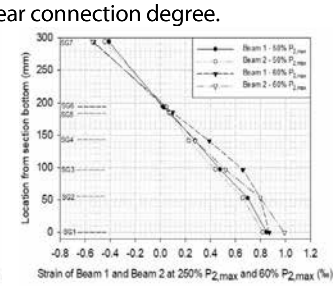


Fig 10. Strain of Beam 1 and 2 at mid-span corresponding 50%$P_{2,max}$ and 60%$P_{2,max}$

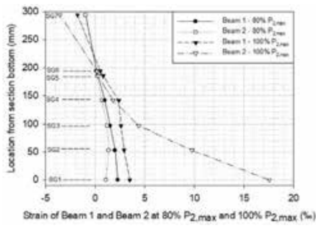


Fig 11. Strain of Beam 1 and 2 at mid-span corresponding 80%$P_{2,max}$ and 100%$P_{2,max}$

3.2 Strain on top and bottom of the steel girder and the concrete slab

The strain on the bottom and top of the concrete slab was measured by strain gauges G6 and G7. These values at failure load are presented in Table 7. The load-strain curves of the concrete slab and steel girder of Beam 1 and 2 are plotted in Figure 12 and Figure 13.

Table 7. The strain of concrete slab

Specimen	Failure load P_{max} (kN)	Bottom surface (‰)	Top surface (‰)
Beam 1	242.22	1.96	-2.37
Beam 2	226.00	0.16	-3.55

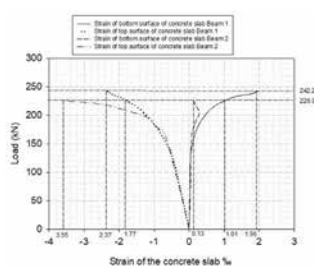


Fig 12. The load-strain curves of the concrete slab of Beam 1 and Beam 2

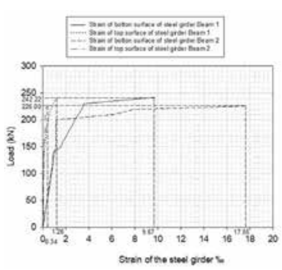


Fig 13. The load-strain curves of the steel girder of Beam 1 and Beam 2

The results showed that the compressive strain of the top surface of the concrete slab of Beam 1 was smaller than that of Beam 2 although the failure load of Beam 1 was higher than the failure load of Beam 2. At the failure load of Beam 2 ($P_{2,max}$ = 226 kN), the strain of the top surface of the concrete slab of Beam 1 was only 1.77‰ (smaller than 2‰) while that of Beam 2 was 3.55‰ (greater than 2‰). This indicated that the steel-concrete composite beam with a higher shear connection degree reduced the compressive strain of the concrete slab.

For the steel girder, whole steel sections are in tension region. The top surface of the steel girder had a lower strain and was smaller than 2‰. The elongation at failure of Beam 1 and Beam 2 was not less than 15% and the value of the elongation at failure of Beam 1 was smaller than that of Beam 2, as shown in Figure 8. This also indicated that the steel-concrete composite beam with a higher shear connection degree reduced the tension strain of the steel girder.

4. CONCLUSIONS

Experimental studying the effect of the shear connection degree on the strain of the steel-concrete composite beams, some suggestions are proposed as follows:

+ The shear connection degree significantly affects the strain of the steel-concrete composite beams.

+ At the low load (about under 80% failure load), the effect of the shear connection degree does not considerably affect the strain of the steel-concrete composite beam.

+ At the higher load level (over 80% failure load) the effect of the shear connection degree on the strain of the steel-concrete composite beam is clear.

+ For beams with higher shear connection degrees, the strain at the top surface of the compressive concrete slab and the strain at the bottom surface of the steel girder is appreciably decreased.

Acknowledgment

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