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Cyclic Performance of Restrained Steel-Concrete Fully Composite Beams Subjected to a Point Load

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ABSTRACT

Composite beams are made of steel sections connected with slabs of concrete held together with shear connectors. The beams enhance the loading capacity and stiffness according to AISC and AASHTO design standards. In this study tests on three restrained steel-concrete full composite beams subjected to a cyclic point load and monotonic loading were conducted and their performances on stiffness, strength, ductility and energy dissipation capacity were analyzed and compared with the results of monotonic loading cases. It was found that the degree of the shear connectors and the type of loading and the position of the load were the major factors influencing the stiffness and cumulative energy dissipation capacity of the full composite restrained steel beams.

Keywords: Cyclic performance, Fully composite, Restrained steel-concrete composite beams

1. INTRODUCTION

Composite structures have been grown for the past decades since Kurpfalz bridge which was the first composite bridge built in 1950[2] in Mannheim of Germany. Bridge design and construction has become increasingly advanced especially steel-concrete composite bridges as they are able to reduce the quantity of steel and the depth of horizontal main beam.

Bridge designs have load capacities which consist of Dead Loads and Live Loads as carried out and comply with AASHTO design standards in order to determine the stiffness of bridge' structures to assure that bridges are strong enough to carry traffic loads in the present and the future. [3,4]

Capacity of force resistance and deformation due to increasing load capacity is complied with the Weight load and Increasing Load capacity international standards under Department of Highway notice. [1] For highway bridges with 40-60 meters, the most efficient beam bridges are composite beam bridges. They consist of steel beams and reinforced slabs of concrete, which are molded on site. The slabs of concrete are connected with shear connectors. Which help by increasing live load capacities.

This research of restrained steel-concrete composite beams under cyclic loading is greatly beneficial for performances on strength, stiffness, ductility, and energy dissipation capacity for Highway bridges design in Thailand.

2. EXPERIMENT

2.1 Steel-concrete full composite beam designs

The steel-concrete fully composite beam is designed in compliance with AASHTO design standards. The Shear connectors in this research are designed to prevent slipping between the surface of the concrete slabs and the steel beams as shown in the Figure 1. Bending movements on the major core assures that the symmetry of the beam is balanced. The compact section with braced ranges in able both wing sides of the beam to receive compressive strength adequately. Torsion and deflection are not seen on the sides.

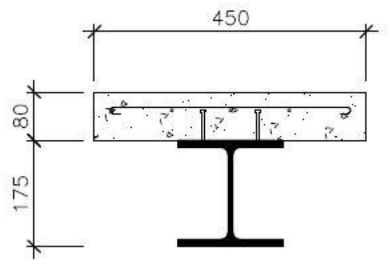

Figure 1: Steel-concrete composite beam SCCB-S1-SM-01, SCCB-S1-CM-02 and SCCB-S1-CP-03.

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Degree of shear connectors, η are an essential factor. Stiffness performance of steel-concrete composite beam as shown in Equation 1.

$$\eta = \frac{n}{n_f} \tag{1}$$

n Numbers of shear connector between Middle point and supports point

n_f Numbers of fully shear force $n_f = \frac{V_s}{V_u}$

V_s Longitudinal shear force unit between steel beam and concrete slabs

V_u Tensile strength of shear connector

The value of degree of shear connector of the fully steel-concrete composite beam is equal to 1.25. The distance of shear connector is 6 centimeters which consists of major beam with the length of 3.80 meters and minor beam with the length of 2.20 meters. There are hinge and roller support in both of them with the strained supports,

Point load, monotonic and cyclic loading at the middle of beam and at the maximum positive moment resistance M^+ as demonstrated in Figure 2 and Figure 3.

2.2 The Material Properties

The test on The Material Properties for restrained steel-concrete fully composite beam is shown in Table 1 and Table 2.

Table 1. The material properties of shear connector

Material	Yield strength (ksc)	Tensile strength (ksc)	Shear strength (ksc)
Shear connectors	3515	4289	3216

Table 2. The material properties of steel beam and reinforced concrete

Material	Yield strength (ksc)	Tensile strength (ksc)
Steel beam	3506	4732
Reinforcement	4750	6858

The loading on steel-concrete composite of restrained beams under monotonic loading is regularly carried with the speed of 1 ton/minute. Similarly, the loading on steel-concrete composite of restrained beams under cyclic loading is also carried with the speed of 1 ton/minute. But with the cyclic loading, each circle is needed to increase by 12% or 0.12 $P_{\max}$ of the maximum load for monotonic loading tests, and after the maximum loading is tested, the loading then is continuously reduced until it reaches zero Tons. The next circles are continued with the same method. In this test, load cells, LVDT transducers and strain gauges are installed to record the loading, the deflection, the rotation on the internal supports, the slip of the concrete slabs at the surface of the steel beams, the strain on the steel beams, v and the strain on the shear connectors, the strain of reinforcement and the strain on the concrete slabs as shown in Figure 4 and Figure 5.

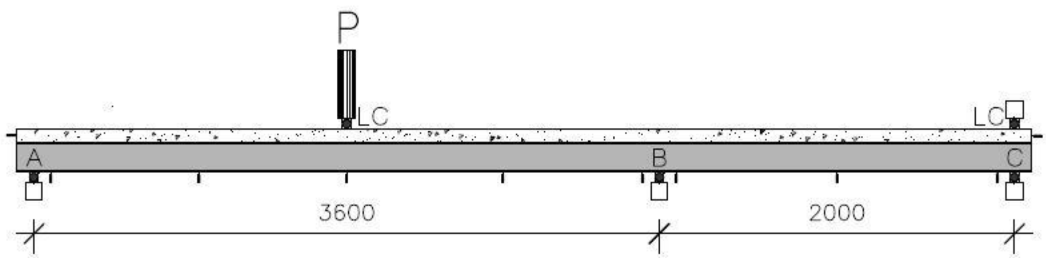

Figure 2. The middle span load on the full steel-concrete composite beam.

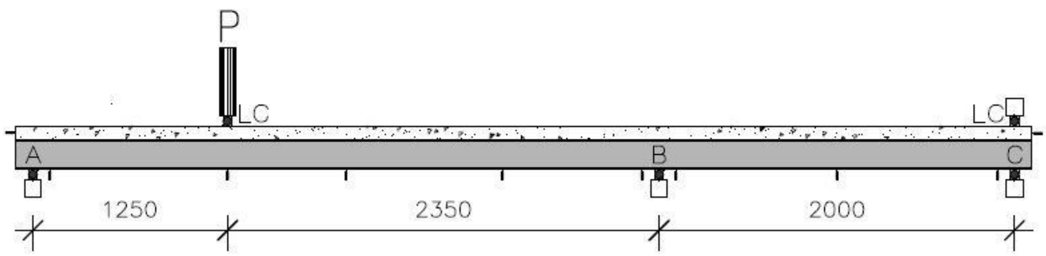

Figure 3. The load a maximum positive moment of sections for the steel concrete fully composite beam.

Figure 4. Steel-concrete composite beam test.

Figure 5. Restrained supports.

The analysis of the load at maximum positive bending moment of cross-sections for the steel concrete fully composite beam under cyclic loading based on Plastic theory has the positive plastic moment of the cross-section M_p^+ at 15.519 Ton-meter and the negative plastic moment of the cross-section M_p^- is equal to 11.290 Ton-meter.

3. THE RESULT AND DISCUSSION

The performance of composite beam under cyclic loading is important for engineering work. Structural bridge design must consider performances on Strength, Stiffness, Ductility, and Energy dissipation capacity for structure stability. [8]

3.1 Strength

The test on strained steel-concrete full composite beams under monotonic and cyclic loading when considering loading points and deflection as shown in the Figure 6, 7, and 8, it is found that the maximum loading of SCCB-S1-CP-03 is equal to 26.03 T. The deflection capacity is equal to 32.10 millimeters. The maximum loading of SCCB-S1-CM-02 is equal to 26.01 T. The deflection of loading is at 3 5 . 8 9 millimeters. The maximum loading of SCCB-S1-SM-01 is equal to 25.85 Tons. The deflection of loading is at 32.93 millimeters and Reinforced concrete failure is shown in the Figure 9 and Steel beams failure at the internal support is shown in the Figure 10. [9]

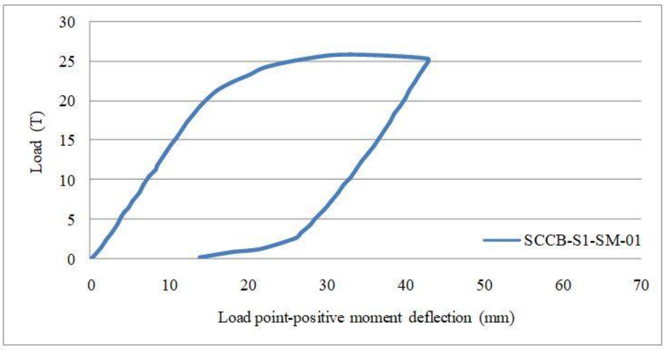

Figure 6. The relationship between loading capacity and deflection capacity SCCB-S1-SM-01.

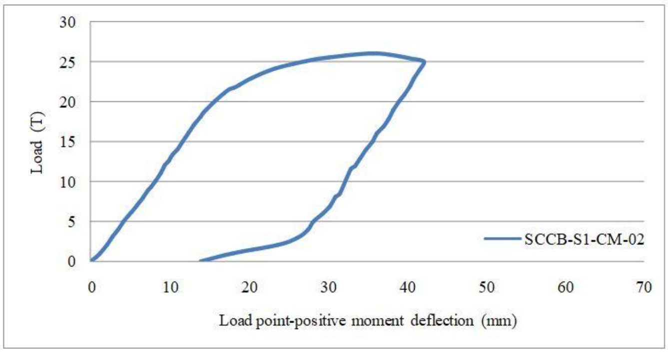

Figure 7. The relationship between loading capacity and deflection capacity SCCB-S1-CM-02

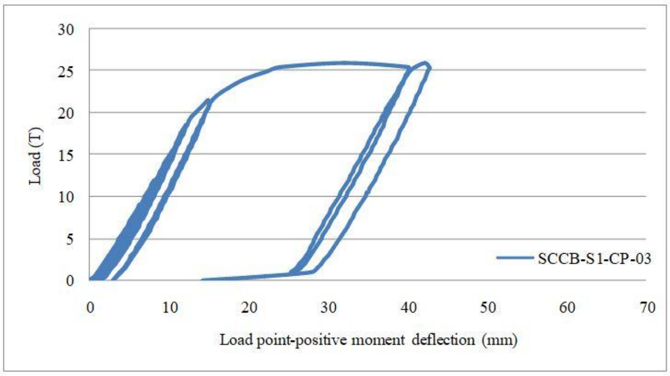

Figure 8. The relationship between loading capacity and deflection capacity SCCB-S1-CP-03.

When strained steel-concrete full composite beams under monotonic and cyclic loading is compared in SCCB-S1-SM-01 and SCCB-S1-CM-02 and SCCB-S1-CP-03 are shown that steel-concrete fully composite beam is able to have more loading at 0.618 and 0.696 percent respectively.

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Figure 9. Reinforced concrete failure SCCB-S1-SM-01.

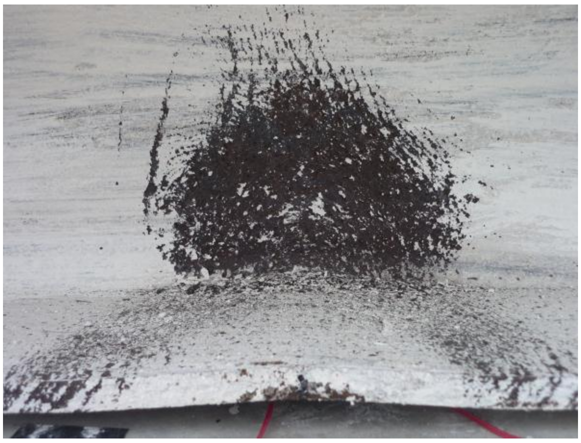

Figure 10. Steel beam failure SCCB-S1-SM-01.

The moment resistance of strained steel-concrete full composite beams under cyclic loading of SCCB-S1-SM-01, SCCB-S1-CM-02, and SCCB-S1-CP-03 has the maximum positive moment resistance M_u^+ which is equal to 18.555, 18.439, and 18.948 Tons-m. The maximum negative moment resistance is equal to 9.903, 9.065, and 3.226 Tons-m. The deflection at loading point Δ_m is equal to 32.93, 35.89 and 32.10 millimeters.

Comparing the bending moment and resistance on strained steel-concrete full composite beams under monotonic and cyclic loading is compared in SCCB-S1-SM-01 with SCCB-S1-CM-02 and SCCB-S1-CP-03. When Enveloped curves of the moment resistance is considered, it is found that steel-concrete full composite beams in SCCB-S1-CM-02 has a positive moment resistance down to 0.625 percent and the negative moment resistance is down to 8.462 percent. For SCCB-S1-CP-03, the positive moment resistance is increased by 2.118 percent and the negative moment resistance is decreased by 67.424 percent due to the loading point and effect on the slope of the bending moment resistance distribution and residual strain result in steel beams as shown in Figure 11.

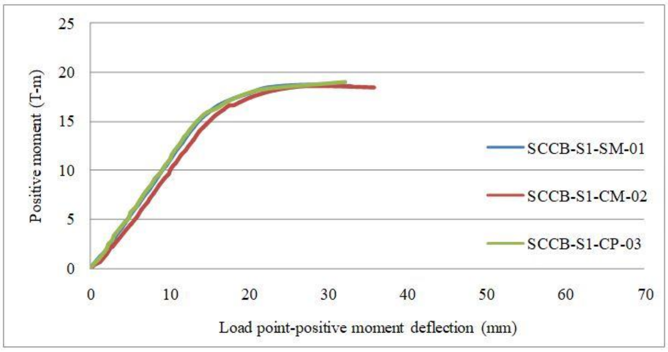

Figure 11. The envelope curves of the moment resistance of steel-concrete fully composite beam.

3.2 Stiffness

A stable structure has the most stiffness in a period of Elastic. When it is forced or receives increases in loads, it leads to deflection and displacement of the structure. Loading capacities from heavier levels to the maximum by stiffness become less strong than in the period of Elastic. Thus, stiffness analysis at the level of loading is necessary to evaluate the beams performance under loading. [8]

Stiffness of strained steel-concrete full composite beams under cyclic loading can be analyzed from the slopes of the bending moment resistance and the angle of Theta $M^+ - \rho$ at the degree of the bending moment resistance as shown in Equation 2.

$$\rho = \frac{\Delta}{l_1} \tag{2}$$

When Δ Deflection of steel-concrete composite beam at loading when cross-section receives the bending moment resistance

l_1 The length of steel-concrete composite beam from supports to the loading position

Stiffness of steel-concrete fully composite beam at yield point of steel beam K_y of SCCB-S1-SM-01, SCCB-S1-CM-02 and SCCB-S1-CP-03 is equal to 1.965x10^3 Ton-meter, 1.758x10^3 Ton-meter and 1.277x10^3 Ton-meter respectively as shown in the Table 3 and Figure 12.

+Stiffness of steel-concrete composite beam

Specimens	K_c	K_y	K_m	K_u
	x10^3 (T-m/rad)			
SCCB-S1-SM-01	1.893	1.965	1.014	0.694
SCCB-S1-CM-02	1.587	1.758	0.924	0.744
SCCB-S1-CP-03	1.249	1.277	0.678	0.501

When K_c Stiffness of beam at the fracture bending moment

K_y Stiffness of beam at the bending moment resistance when steel beam is getting yield

K_m Stiffness of beam at the maximum bending moment resistance

K_u Stiffness of beam at the tensile bending moment

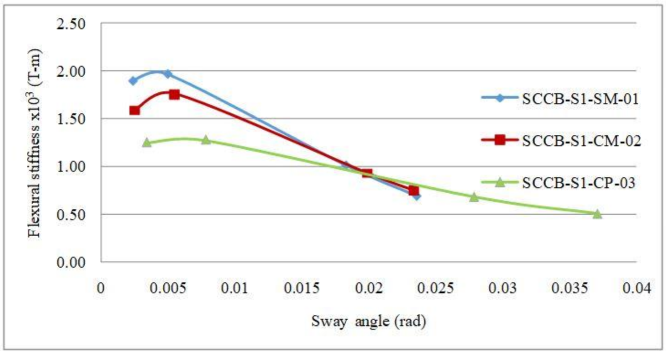

Figure 12. Stiffness of steel-concrete fully composite beam.

Comparing on stiffness of strained steel-concrete full composite beams under monotonic and cyclic loading at the moment resistance when steel beams are getting yield in SCCB-S1-SM-01 and SCCB-S1-CM-02 and SCCB-S1-CP-03, it is found that stiffness of steel-concrete full composite beam is decreased by 10.534 and 35.012 percent. For stiffness of strained steel-concrete full composite beam under monotonic and cyclic loading at the maximum bending moment resistance in SCCB-S1-SM-01 and SCCB-S1-CM-02 and SCCB-S1-CP-03, it is shown that stiffness of steel-concrete full composite beams are decreased by 8.875 and 33.136 percent respectively.

Comparison of stiffness of steel-concrete composite beam to the research study of Nie and Cai. (2003), Zhao et al. (2012), Souici et al. (2013) and Fa-Xing Ding et al. (2016) with SCCB-S1-SM-01, it shows that stiffness of strained steel-concrete full composite beam with monotonic loading at the bending moment resistance when steel beam is getting yield is increased by 31.704, 63.511, 61.272 and 22.697 percent. And when consider stiffness with cyclic loading of SCCB-S1-CM-02 with CB3, SCB1, B1 and S C B 8 , it is found that the stiffness of steel-concrete fully composite beam is increased by 23.663, 59.21, 56.712 and 13.594 percent. Moreover, stiffness under cyclic loading of SCCB-S1-CP-03 with SCB1 and B1 is found that steel-concrete fully composite beam is increased by 43.852 and 40.407 percent. Besides, steel-concrete composite beam of SCCB-S1-CP-03 with CB3 and SCB8 is found that stiffness of steel-concrete fully composite beam is decreased by 5.090 and 18.950 percent.

For stiffness of strained steel-concrete fully composite beam under monotonic loading at the maximum bending moment resistance K_m is increased by 67.455, 65.384, 77.218 and 35.108 percent. And when consider stiffness of cyclic loading of SCCB-S1-CM-02 with CB3, SCB1, B1 and S C B 8 , it is found that stiffness of steel-concrete fully composite beam is increased by 64.285, 62.012, 75.000 and 28.787 percent. Moreover, stiffness of cyclic loading of SCCB-S1-CP-03 with CB3, SCB1, B1 and S C B 8 is found that stiffness of steel-concrete fully composite beam is increased by 51.327, 48.230, 65.929 and 2.949 percent. The index of shear connector between reinforced slab concrete and steel beam under monotonic and cyclic loading has overall effects on stiffness capacity of beam.

Table 4. Stiffness comparison of steel-concrete composite beam

Source of the specimens	No.	Loading mode	η	K_y x10³ (T-m/rad)	K_m x10³ (T-m/rad)
This paper	SCCB-S1-SM-01	monotonic	1.25	1.965	1.014
	SCCB-S1-CM-02	cyclic	1.25	1.758	0.924
	SCCB-S1-CP-03	cyclic	1.25	1.277	0.678
Nie and Cai 2003	CB3	monotonic	1.02	1.342	0.330
Zhao et al. 2012	SCB1	monotonic	1.10	0.717	0.351
Souici et al. 2013	B1	monotonic	0.73	0.761	0.231
Fa-Xing Ding et al. 2016	SCB8	monotonic	1.32	1.519	0.658

3.3 Ductility ratio (R')

Ductility ratio or deformation capacity of steel-concrete composite beam can be calculated as shown from Equation 3 below. [10]

$$R' = \frac{\Delta^{+}_{\max}}{\Delta_p} - 1 \qquad (3)$$

When R' Ductility ratio or deformation Capacity.

$\Delta^{+}_{\max}$ Deflection of steel-concrete composite beam at loading when cross-section receives the bending moment resistance over the position of the maximum bending moment resistance.

Δ_p Deflection of steel-concrete composite beam at loading when cross-section receives Plastic moment resistance from Elastic bending.

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Ductility ratio of strained steel-concrete fully composite beam under cyclic loading is found that ductility ratio R' of steel-concrete fully composite beam of SCCB-S1-SM-01, SCCB-S1-CM-02 and SCCB-S1-CP-03 is equal to 2.019, 1.690 and 2.059 respectively. The ductility ratio average is equal to 1.923 as shown in Table 5.

Table 5. Ductility ratio of steel-concrete fully composite beam

Specimens	Δ_p (mm)	$\Delta_{\max}$ (mm)	R'
S1-SM-01	14.20	42.88	2.019
S1-CM-02	15.88	42.71	1.690
S1-CP-03	13.96	42.72	2.059

When the ductility ratio of strained steel-concrete fully beam under monotonic loading is compared, it is found that the ductility ratio of strained steel-concrete fully composite beam with cyclic loading of SCCB-S1-CM-02 is decreased by 16.295 percent and the ductility ratio of strained steel-concrete fully composite beam under cyclic loading of SCCB-S1-CP-03 is increased by 1.981 percent.

3.4 Energy dissipation capacity

Energy dissipation capacity of structure is a key index that indicates the performance of structure which depends on all structural elements. In case of cyclic loading, it is required to evaluate cumulative energy dissipation capacity under cyclic loading in order to decrease effectiveness of cumulative damages that occurs to structures. [6]

Strained steel-concrete fully composite beam under monotonic and cyclic loading at yielding point E_y of SCCB-S1-SM-01, SCCB-S1-CM-02 and SCCB-S1-CP-03, it is found that energy dissipation capacity is equal to 0.02517 Ton-meter, 0.02031 Ton-meter and 0.03338 Ton-meter. For strained steel-concrete fully composite beam under monotonic and cyclic loading at the maximum bending moment resistance E_m of SCCB-S1-SM-01, SCCB-S1-CM-02 and SCCB-S1-CP-03, it is found that energy dissipation capacity is equal to 0.34662 Ton-meter, 0.30327 Ton-meter and 0.50943 Ton-meter as shown in the Table 6 and Figure 13.

Table 6. Cumulative energy dissipation capacity of steel-concrete fully composite beam

Specimens	Cumulative energy dissipation capacity		
	E_c (T-m)	E_y (T-m)	E_m (T-m)
S1-SM-01	0.00516	0.02517	0.34662
S1-CM-02	0.00559	0.02031	0.30327
S1-CP-03	0.00885	0.03338	0.50943

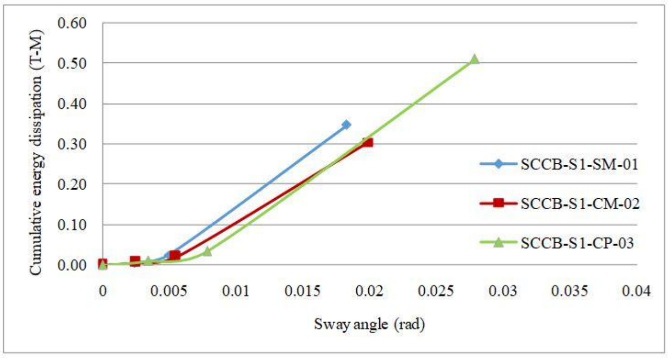

Figure 13. Cumulative energy dissipation capacity of steel-concrete fully composite beam

Comparing on strained steel-concrete fully composite beam under monotonic and cyclic loading at the maximum moment resistance in SCCB-S1-SM-01 and SCCB-S1-CM-02 and SCCB-S1-CP-03, it is found that steel-concrete fully composite beam has decreased energy dissipation capacity by 12.506 percent and SCCB-S1-CM-03 has increased energy dissipation capacity by 46.970 percent.

4. CONCLUSION

From the result of the study on performance of restrained steel-concrete fully composite beam under cyclic loading, it can be summarized as follow;

1. The moment resistance of the strained steel-concrete fully composite beam under cyclic loading has the positive moment more than monotonic loading. The maximum positive moment M_u^+ is equal to 0.743 percent and cyclic loading has the negative moment less than monotonic loading. The maximum negative moment M_u^- is equal to 37.943 percent. The deflection under cyclic loading is higher than deflection under monotonic loading. The average of deflection Δ_m is equal to 3.173 percent.
2. Stiffness of strained steel-concrete fully composite beam under monotonic and cyclic loading at the bending moment resistance when steel beam is getting yield in SCCB-S1-SM-01 and SCCB-S1-CM-02 and SCCB-S1-CP-03, it is found that the stiffness of steel-concrete full composite beam is down to 10.534 and 35.012 percent. For the stiffness of strained steel-concrete fully composite beam under monotonic and cyclic loading at the maximum moment resistance in SCCB-S1-SM-01 and SCCB-S1-CM-02 and SCCB-S1-CP-03, it is found that the stiffness of steel-concrete fully composite beam is down to 8.875 and 33.136 percent.
3. Stiffness of strained steel-concrete fully composite beam under monotonic loading is found that strained steel-concrete fully composite beam under cyclic loading when compared with SCCB-S1-SM-01. It is shown that the stiffness ratio of SCCB-S1-CM-02 is decreased by 16.295 percent and the stiffness ratio of SCCB-S1-CP-03 is increased by 1.981 percent.
4. Cumulative energy dissipation capacity of restrained steel-concrete fully composite beam under cyclic loading when compared with SCCB-S1-SM-01. It is found that

the energy dissipation capacity of SCCB-S1-SM-01 is reduced by 12.506 percent and the energy dissipation capacity of SCCB-S1-CM-03 is increased by 46.970 percent.

From the research study, it is found that degree of shear connector, position of load capacity and restrained supports are essential key factors which have influence on performance of the strained steel-concrete fully composite beam under cyclic loading.

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