Numerical Analysis of Continuous Composite Steel Girders with Partial Composite Action Strengthened by CFRP

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ABSTRACT: The composite steel-concrete girder depends mainly on the composite action between steel beam and concrete slab. Composite action forms by providing shear connectors between steel beam and concrete slab whereas composite action level depends on the amount of the transferred horizontal shear force. This paper presents numerical investigation of continuous steel-concrete composite girders with different levels of shear connection at negative moment region. CFRP sheets were bonded to the top of concrete slab at the negative moment region. Finite element (FE) results were compared with experimental results and showed close agreement. FE results showed that the increase of shear connection level beyond the full composite action had slight effect on the performance of continuous composite girders. Ultimate load capacity and deflection at girder mid span were increased by the increase of the shear connection level at negative moment region. Interface slip between top flange of steel beam and bottom of concrete slab was directly proportional to the shear connection level. Higher shear connection level resulted in higher longitudinal stress in CFRP sheet bonded to the top of concrete slab at the negative moment region.

1 INTRODUCTION

Composite steel-concrete girders are commonly used in bridges and buildings. It composed of cast in place concrete slab and steel beam. The components of steel-concrete girders act independently and interface slip occurs under the load effect, if there is no connection between them. Shear connectors can be used between concrete slab and steel beam to prevent slipping under the effect of tangential shear force. Composite construction efficiently utilizes the materials properties and reduces construction cost. In continuous composite girders, negative moment at internal support region will generate tensile stress in concrete slab. Composite action between concrete slab and steel beam may be lost under the effect of tensile stresses causing cracks of concrete slab. This work presents use of CFRP sheets bonded to the top of concrete slab to maintain the composite action at negative moment region. Sharif & Samaaneh (2014) investigated numerically the behavior of continuous composite girders with full composite action with CFRP bonded at negative moment region under static load. The results showed that bond of CFRP at negative moment region improved the strength and stiffness of continuous composite girder. The extending CFRP beyond the inflection points eliminated any premature failure. Loh et al (2004) conducted an experimental work on three composite beams to investigate their behavior under negative moment. The specimens were designed with different levels of shear connection and tested under static loading. The results showed that moment capacity slightly increased with increasing shear connection level while the ductility decreased. Fabbrocino & Pecce (2000) studied experimentally the behavior of three simply supported steel-concrete composite beams subjected to negative moment. Two beams had same design interaction level with different arrangement while third one designed with partial interaction level. The behavior of the beams was investigated under the influence of slab-profile shear connection. Nie et al (2008) tested thirteen steel-concrete composite beams with different levels of shear connections. Some of the beams were tested as simply supported beams under positive and negative moments and other specimens were tested as continuous beams with two and three spans. The results showed that the failure mode of specimens with shear connection level less than 50% was governed by studs rupture while the concrete of specimens with more than 50% shear connections was crushed. As the shear connection level decreased, the beam capacity and ductility reduced. Also, the curvature and deflection were increased significantly when the load exceeded 80% of ultimate load.

This paper numerically evaluates the performance of continuous composite girders with different shear studs spacing at the negative moment region. The behavior of continuous composite girders was studied with presence of CFRP sheets bonded to the top of concrete slab at negative moment region. Finite element modeling was conducted on two span continuous girders using ABAQUS software. The study focused on the interface slip between steel beam and concrete slab, composite girder deflection and stiffness, CFRP stress and girder ultimate load capacity.

2 MODELED GIRDERS

The numerical study was conducted on continuous steel-concrete composite girders. Two spans girders were analyzed as that in the experimental work to validate the results. Two spans were used to produce one negative moment region over the interior support where this type of girders is widely used in bridges construction. The dimension and cross section of the composite girder are shown in Figure 1. One point of loading was applied at the mid of each span. All girders were with same shear studs spacing at positive moment region while each girder had different shear studs spacing at negative moment region as shown in Table 1. G-16.5 and G-10 designed with partial composite action while G-7.5 and G-6 had full composite action at negative moment region. Shear studs of 19mm diameter and 50mm in length were used. All girders were strengthened with two layers of unidirectional CFRP sheets at negative moment region. Moreover, concrete slab was wrapped with CFRP sheet under the load at positive moment region as shown in Figure 2.

Load-slip relationship for shear studs is presented in Figure 3. The stress-strain diagram of steel plate, steel reinforcement, and concrete are shown in Figure 4 and Figure 5. CFRP was bonded to concrete slab using epoxy adhesive. The properties of epoxy adhesive and CFRP is summarized in Table 2.

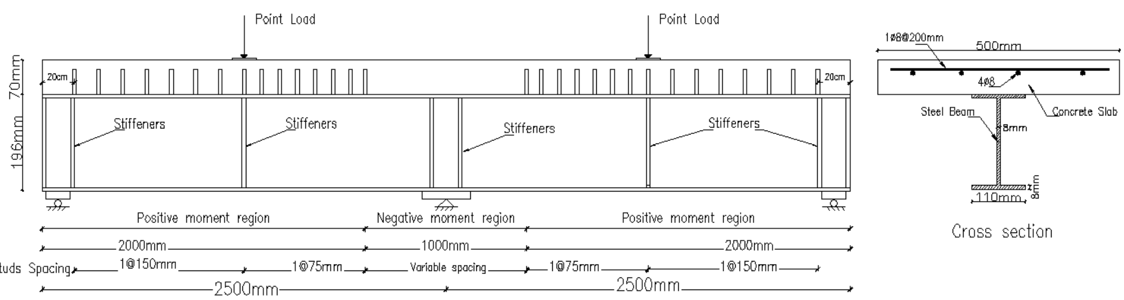

Figure 1. Geometry of composite girder and shear studs spacing

Table 1. Shear stud spacings at negative moment region

Specimens	Studs spacing at negative moment region
G-16.5	1@165mm
G-10	1@100mm
G-7.5	1@75mm
G-6	1@60mm

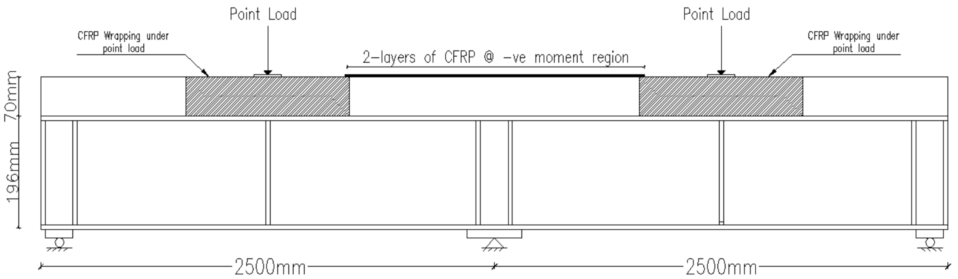

Figure 2. CFRP sheets locations

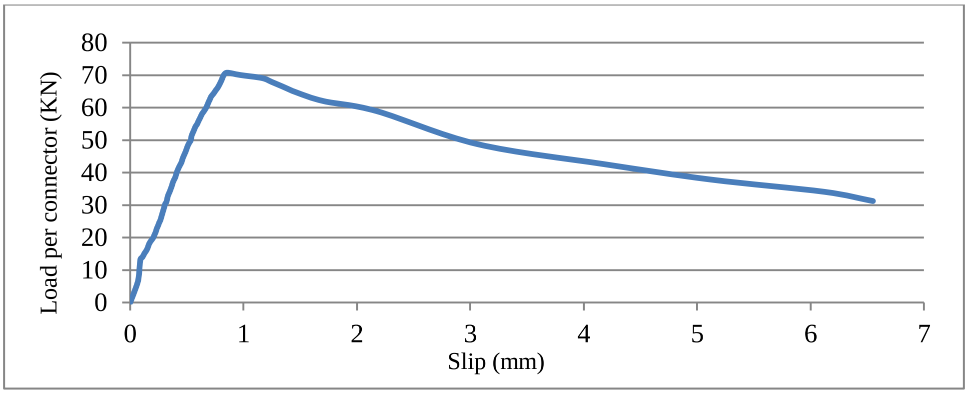

Figure 3. Load-slip relationship of shear studs

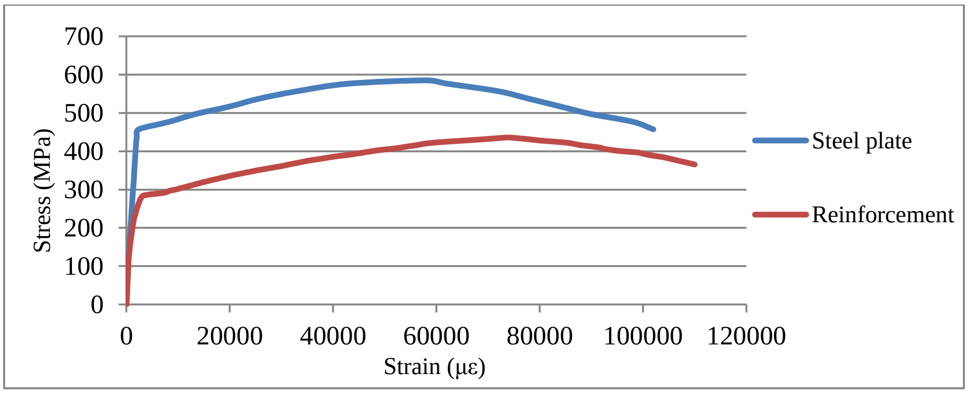

Figure 4. Stress-strain diagram of steel plate and reinforcement

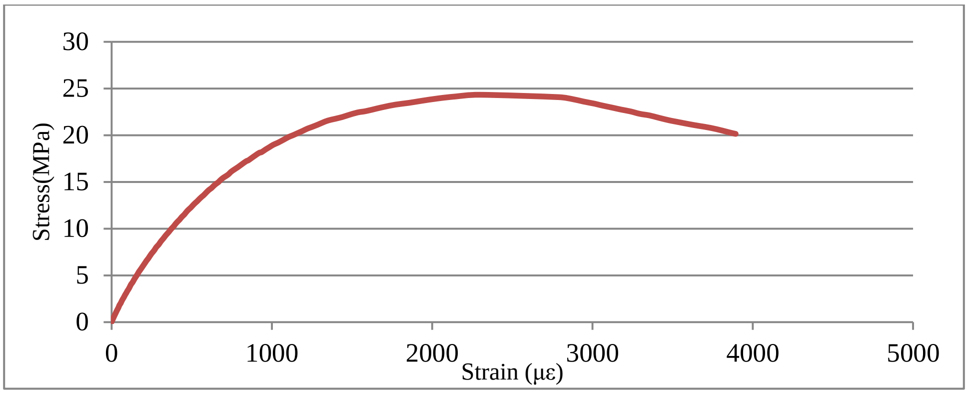

Figure 5. Stress strain diagram of concrete

Table 2. CFRP and epoxy properties

Properties of CFRP		Properties of Epoxy	
Fiber density	$1.8 g/cm^3$	Tensile strength	30MPa
Tensile strength	3500MPa	Shear strength	22MPa
Tensile modulus	230GPa	Flexural modulus	3800MPa
Elongation at break	2.1%	Tensile modulus	4500MPa

3 FINITE ELEMENT MODELING

A non-linear finite element model was created using ABAQUS 6.13-1 software to investigate the behavior of continuous steel-concrete composite girder. Composite girders were analyzed with different shear studs spacing at negative moment region which bonded with CFRP sheets to the top of concrete slab. The ABAQUS model of the continuous composite girder is shown Figure 6 and model meshing is shown in Figure 7.

The steel beam, concrete slab, and shear studs modeled using 3D stress 8-node linear brick element (C3D8R) with a reduced integration and hourglass control. Steel reinforcement modeled using 2-node linear 3-D truss element (T3D2). CFRP modeled using 4-node doubly curved thin or thick shell element (S4R) with a reduced integration, hourglass control, and finite membrane strains.

The steel material; steel beam and reinforcement, and shear studs were defined as an elasto-plastic material. The concrete was modeled with an initial linear-elastic material up to 30% of its compressive strength then it was represented by concrete damage plasticity model (CDP) in plastic range. When it subjected to tension, the concrete stress is assumed to increase linearly till its tensile strength is reached. CFRP was modeled as uni-directional laminate and its material was defined as linear elastic material.

The interaction between steel and concrete was modeled using surface to surface contact. Steel reinforcement was defined as embedded region inside concrete. The contact between shear studs and concrete was defined as mechanical interaction using friction formulation in tangential direction. Friction coefficient was specified as 0.5, and maximum shear stress was defined according load-slip curve. Cohesive contact was used to simulate the behavior of adhesive material between the concrete and CFRP, the values of normal and tangential stiffness were provided as input data.

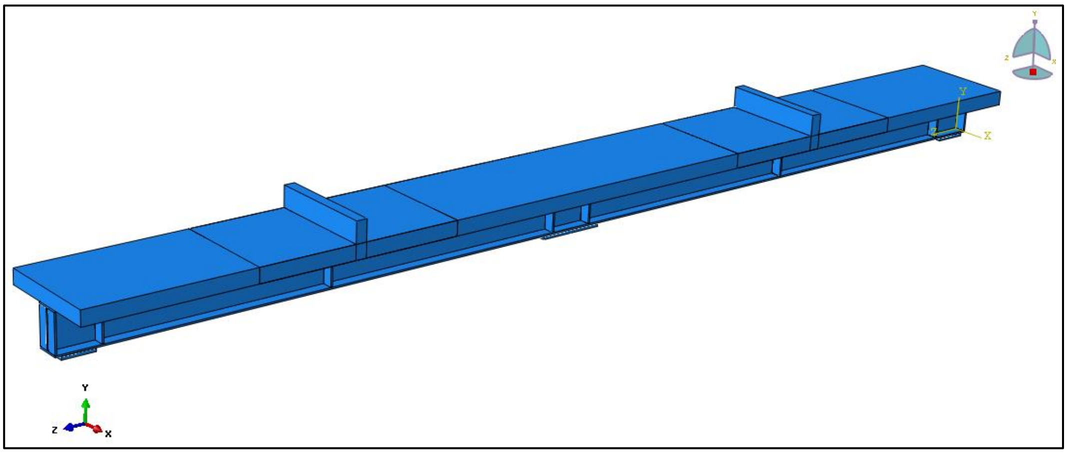

Figure 6. The geometry modeled girders

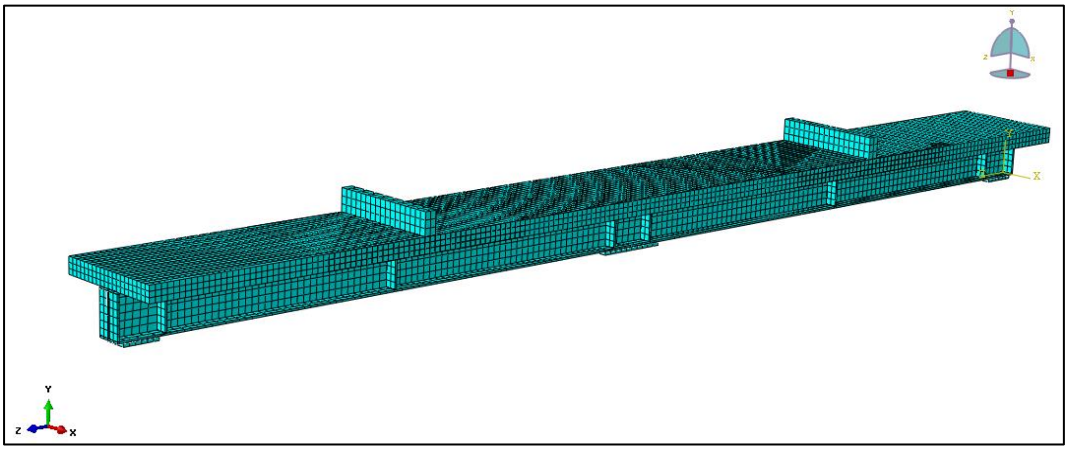

Figure 7. Overview of the assembled and meshed model

4 RESULTS AND DISCUSSION

4.1 Verification of the model

The finite element results were verified with the experimental results of composite girder conducted for this research. The finite element results showed good correlation with the experimental results. Figure 8 shows comparison between experimental and numerical load deflection curves for girder G-16.5. The difference in load capacity is within 5%, and deflection is within 10%.

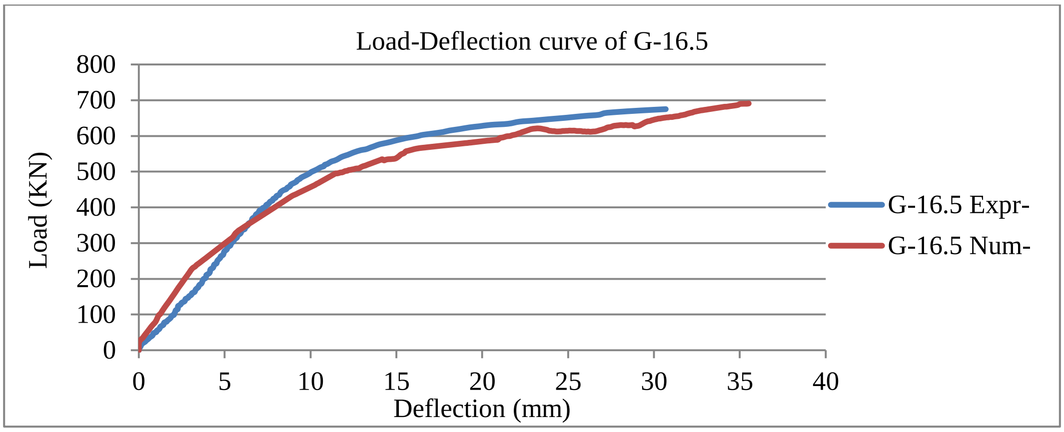

Figure 8. Load-Deflection curve of G-16.5

4.2 Load capacity and deflection

Figure 9 shows the load deflection curve of G-6, G-7.5, G-10, and G-16.5. It was noted that the load capacity of the girders were increased with reducing the shear studs spacing at negative moment region i.e, load capacity was increased with higher shear connection level. Girders with higher level of shear connection behaved more flexible such that deflection increased as shear studs spacing at negative moment region was reduced. Toughness of the different girders is shown in Table 3. The toughness increased with increasing the shear connection level. No considerable effect of increasing the shear connection level beyond the full composite action. Table 3 presents summary for ultimate load capacity, deflection, and toughness for all girders.

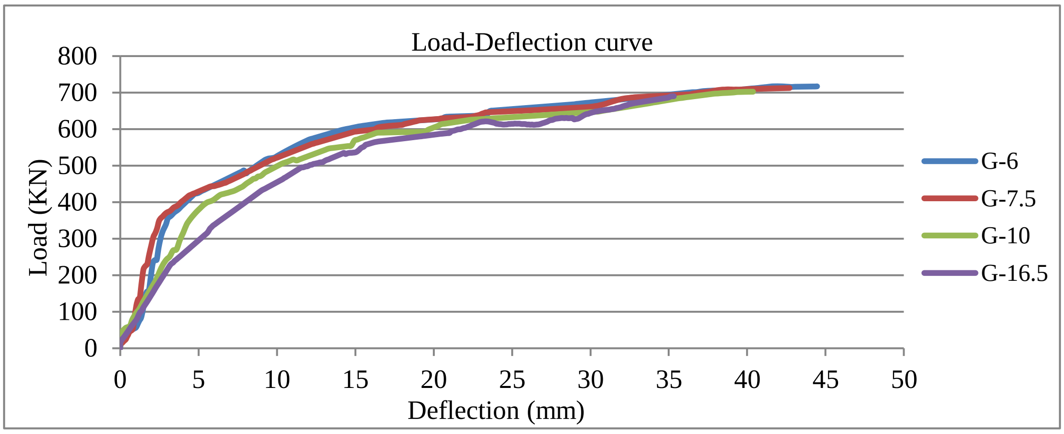

Figure 9. Load-deflection curve for all girders

Table 3. Summary of girders results

	G-16.5	G-10	G-7.5	G-6
Ultimate load (KN)	690	702	712	717
Deflection at ultimate load (mm)	35.2	40.26	42.8	43.7
Toughness (KN.mm)	16169	19653	22486	23133

4.3 Interface slip

The interface slip between top flange of steel beam and bottom of concrete slab during loading process at negative moment region is presented in Figure 10. It was noted that the slip was very small at the early stages of loading up to 50% of ultimate load then developed rapidly up to failure load. Therefore, the increasing of shear studs spacing caused more slip which can be observed clearly in girder G-16.5. Girders G-6 and G-7.5 had close load slip performance where both had full composite action at negative moment region. The interface slip might be influenced by cracking of concrete slab at the negative moment region. Increasing of shear studs spacing in that region caused wider and longer cracks which increased the interface slip.

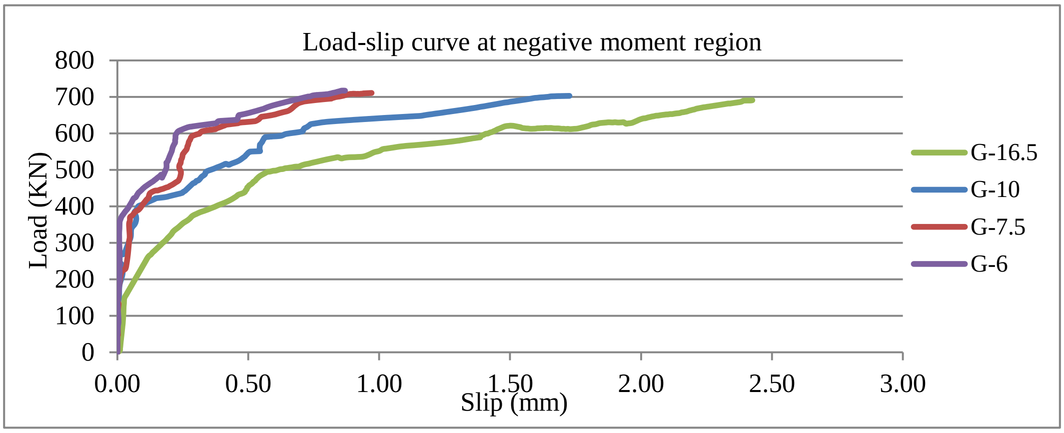

Figure 10. Load-slip curve at negative moment region

4.4 CFRP stress

Longitudinal stress in CFRP at negative moment region was affected by shear connection level. It was observed that the increasing of shear connection level leaded to increase the stress value developed in CFRP sheets. This is because the increase of shear connection level allowed providing more shear studs at negative moment region and increased the ability to transfer higher tangential shear force. Therefore, higher stress value developed in CFRP. The maximum stress was at the interior support and decreased gradually to the mid span. Figure 11 displays the stresses developed in CFRP for girder G-16.5.

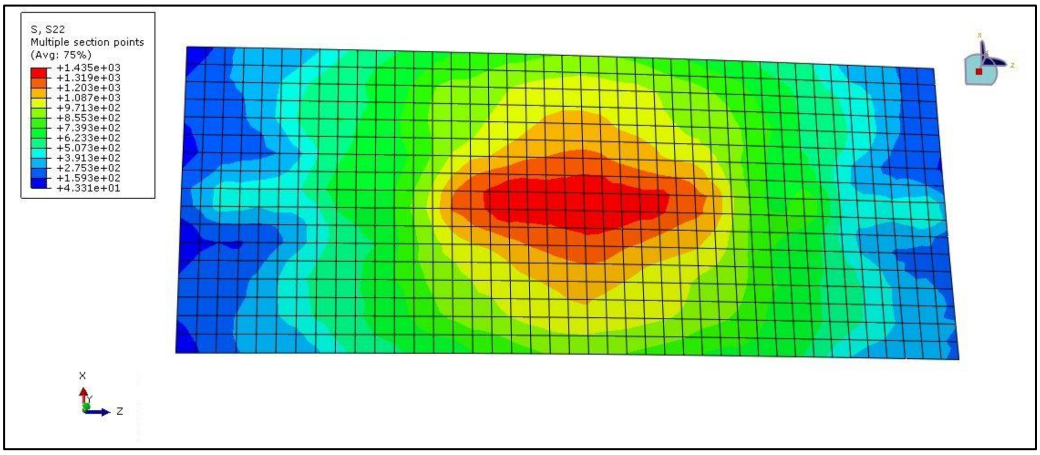

Figure 11. Stresses developed in CFRP of G-16.5

5 CONCLUSION

Numerical investigation was carried out on continuous composite girders with variable shear studs spacing at negative moment regions. CFRP was bonded to the top of concrete slab at negative moment region. The effects of shear studs spacing were discussed through load-deflection curves, interface slip, and CFRP performance. From the numerical analysis results, the following conclusions were made.

- Finite element results were verified and showed close agreement with the experimental results.
- Shear connection level at negative moment region slightly affected the load carrying capacity as well as mid span deflection where it increased with the increase of shear connection level.
- For high level of shear connection, the continuous composite girders exhibited slight increase of stiffness
- The increase of shear connection level at negative moment region reduced the interface slip between concrete slab and steel beam.
- The increase of shear of shear connection level at negative moment region allowed to transfer higher tangential shear force between concrete slab and steel beam, so the stress developed in CFRP increased with the increase of shear connection level.

6 ACKNOWLEDGEMENT

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