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Simulation of ability of CFRP to reinforce continuous composite girders using contact model

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ABSTRACT: The composite concrete-steel girders have efficiently used material capabilities for simple span girders. For continuous composite girders, concrete slab over the interior supports will be under tension and consequently loses its contribution to the composite action. Typical design codes ignore the contribution of concrete slab at the negative moment region for continuous composite girders or consider the steel reinforcements of concrete slab to act compositely with the steel section. For both options, capacity at the negative moment region is greatly reduced.

Numerical investigation of ability of carbon fiber reinforced polymer (CFRP) sheets to maintain the steel-concrete composite action at the negative moment region is intended in this paper. A three dimensional nonlinear Finite element (FE) modelling is carried out in this study using commercial software ABAQUS. Four girders of different thicknesses of CFRP at the negative moment region are investigated in this study. CFRP sheet is bonded to the top of concrete slab at the negative moment region and extended for a certain development length. The composite girders are designed to be fully composite between concrete and steel beam by using of mechanical shear studs. Concrete damage plasticity is used for modeling concrete. Contact models are used to simulate the composite action between CFRP and concrete slab, and concrete slab and shear studs. The numerical results validated with experimental results and showed good agreement.

1 INTRODUCTION

Composite concrete-steel girders are typically used in buildings and bridges. The concrete slab at the negative moment region is ignored and steel girder either acts alone or compositely with slab reinforcement. Concrete cracking over the interior supports reduces stiffness and ultimate strength of composite girders. Different techniques have been used to increase the capacity of continuous composite girders. External and internal prestressing of continuous composite girder were used to increase capacity and stiffness at negative moment region (Basu et al 1987 & Chen et al 2009). Both studies have resulted in strength and stiffness improvement of the continuous composite girder. Recently, CFRP sheets and plates are widely used in strengthening structures. The use of CFRP offered an attractive solution because of high tensile strength of this material and long serviceability time. Several researchers have used CFRP to improve strength of concrete, steel, and composite structures (Miller et al. 2001; Ibrahim and Mahmood 2009; Quantrill and Hollaway 1998; Kasimzade and Tuhta 2012).

FE analysis is efficient and economical method of evaluation and investigation behavior of structures. Researchers have been used FE software to evaluate behavior of concrete structures strengthened by CFRP. Evaluation of the concrete-CFRP interface is also included to cover all typical types of failure that could happen for CFRP (Obaidat et al 2010; Pešić, and Pilakoutas 2003; Totry et al 2010; Nour et al 2007). Numerically evaluation of the effect of bonding CFRP sheet to the top of concrete slab at the negative moment region for two spans continuous composite girders is investigated in this paper. Commercial FE software ABAQUS is used to conduct Finite element modeling. The numerical results are validated with the experimental results obtained from the same project (Project IN121053, DSR-KFUPM). The thickness of CFRP is varied to evaluate the effect of CFRP thickness on the behavior of composite girders.

2 FINITE ELEMENT MODELING

2.1 Definition of continuous composite girder

2.1.1 Geometry of girder

The modeled continuous composite girder is illustrated in Figure. 1. Typical concrete-steel cross section is used for all girders as shown in Figure. 2. Total of four girders have been modeled in this study. Girder RG is considered as control girder without CFRP at the negative moment region. The other three girders called G-1, G-2, and G-3 are bonded with three different thicknesses of CFRP (0.131, 0.262, and 0.393 mm respectively). Shear studs of 19 mm diameter are used to compose the composite action between concrete and steel. The composite girders are monotonically loaded by a point load at each span as shown in Figure 1.

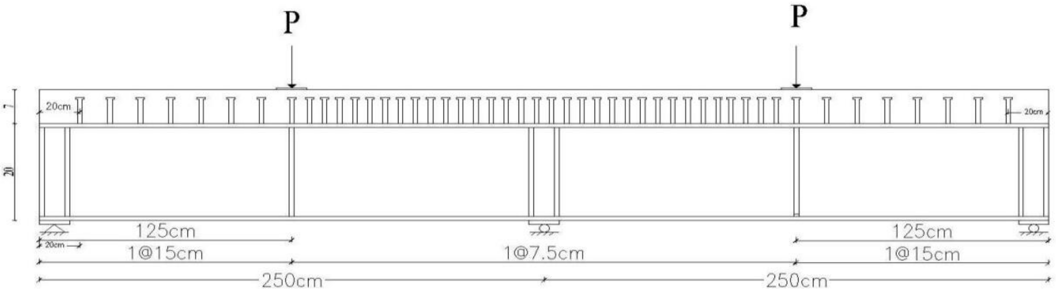


Figure 1. Geometry of modeled girder

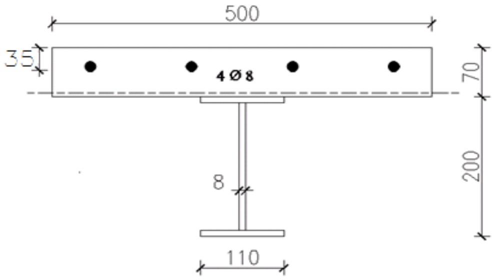
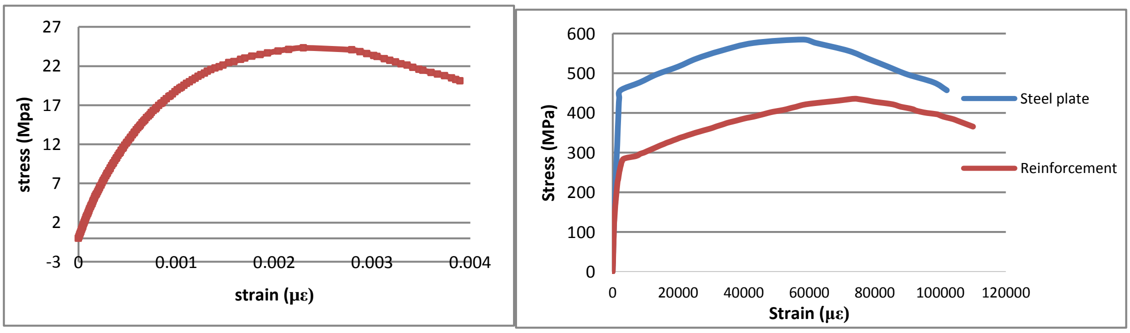


Figure 2. Cross section Dimensions (cm)

2.1.2 Materials

The stress-strain curves of concrete, steel, and steel reinforcement are shown in Figure 3a&3b. Unidirectional CFRP of 0.131 mm thickness and 500 mm width is used to strengthen composite steel-concrete girders. Mechanical properties of concrete, steel, steel reinforcement and CFRP are summarized in Table 1. The mechanical properties of material are obtained from the experimental testing of girders conducted in the same project. The load-slip curves of shear studs and epoxy adhesive are obtained using push-out test. Those curves are needed to simulate the concrete-steel and concrete-CFRP contacts.



a. Concrete b. Steel and steel reinforcement

Figure 3 Stress-strain diagrams

Table 1. Mechanical properties of materials

Concrete		CFRP	
Compressive strength	26.4 MPa	Tensile strength	3483 MPa
Young Modulus	23.800 GPa	Ultimate strain	0.015
Poissons' ratio	0.199	Young Modulus	232.2 GPa
Strain at ultimate	0.0028	Density	1.8 gm/cm^3
Strain at failure	0.0037	Thickness	0.131 mm
	Steel	Steel Reinforcement	
Yield strength (MPa)	278.6	417.7	
Ultimate strength (MPa)	430.7	601.3	
Poissons' ratio	0.291	0.301	
Young Modulus (GPa)	205	205	

2.2 Modeling of composite girders

2.2.1 Modeling of composite girder elements

Isotropic plasticity model and concrete damage plasticity model are used to model concrete. The plasticity model adopts the yield function proposed by Lubliner et al. (1989) and modified by Lee & Fenves (1998) and follows a non-associated flow rule. Plastic model parameters associated with concrete are given in Table 2. The response of degraded concrete is presented by two independent uniaxial damage variables, d_t and d_c which are assumed to be functions of the plastic strains. Those parameters are calculated by use of loading-unloading compression and tension tests

Table 2. Plastic model parameters of concrete

Young Modulus	Poissons' ratio	Dilation Angle	Eccentricity	F_{bo}/F_{co}	K	Viscosity parameter
23800 MPa	0.199	36	0.1	1.16	0.67	0

Steel, steel reinforcements, and shear studs are modeled using isotropic plasticity model. Stress-plastic strains are obtained using stress-strain curves shown earlier, and used as input data for the model. CFRP modeled as a composite uni-directional laminate. Thickness of 0.131 mm for each layer is used, and modulus of elasticity of matrix (CFRP and primer) is used for material definition. CFRP is modeled as linear elastic material. The modeled composite girder is shown in Figure 4.

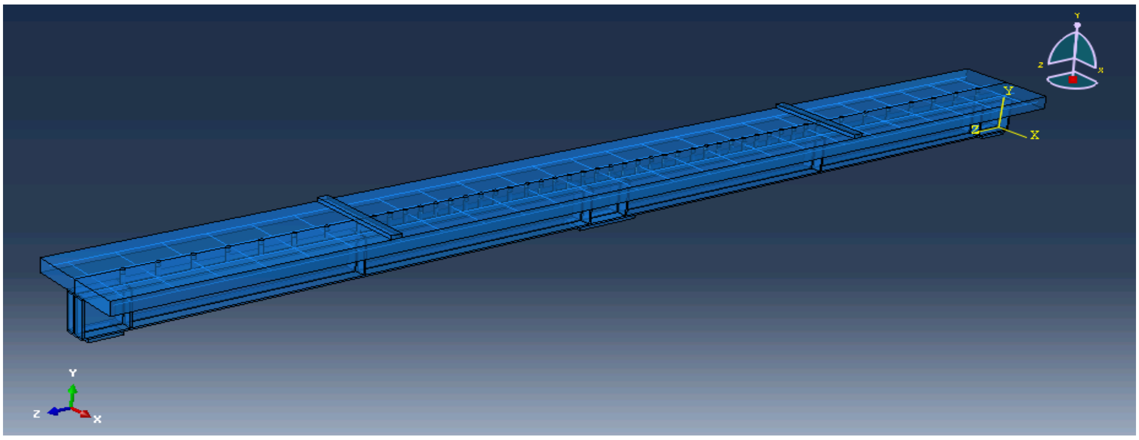


Figure 4. ABAQUS view of the modeled girder

2.2.2 Element type and mesh

Eight-node linear brick element (C3D8R) is used to model the solid elements; concrete, steel, and shear studs whereas steel reinforcement modeled as 2-node linear 3-D truss (T3D2). A 4-node doubly curved thin or thick shell (S4R) is used to model CFRP.

Results accuracy depends upon the finite element mesh, constitutive material model and the boundary conditions. Adequate attention has been paid in the development of hexa-dominated mesh and assigning interaction between various surfaces. The components of composite girder are meshed using part by part basis instead of using global or sweep features. Thus a regular structured hex-dominated mesh is generated. Adequate mesh size has been adapted as shown in Figure 5 to ensure accuracy of results.

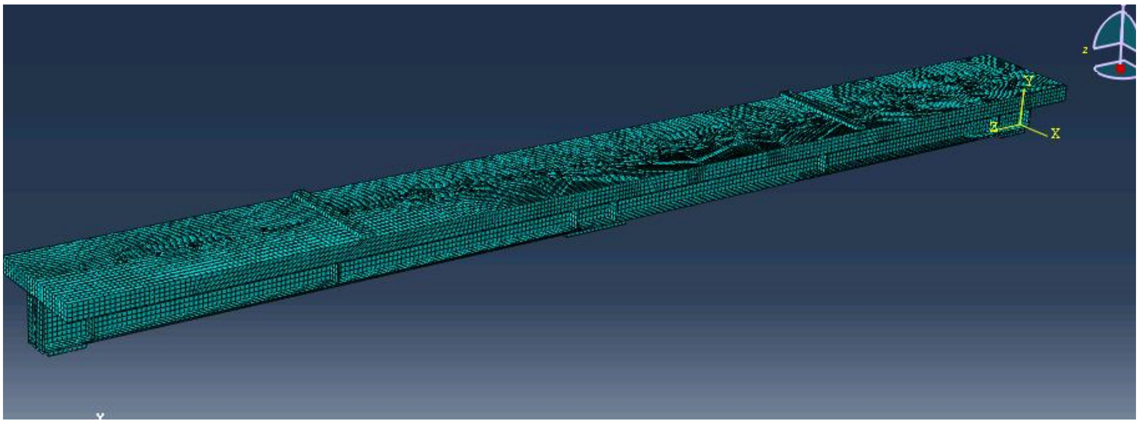


Figure 5. Meshing of modeled girders

2.2.3 Modeling of interfacial regions

Surface-surface contact is used to define the concrete-steel interaction. Mechanical interaction between the stud and concrete surfaces is modelled using friction formulation in tangential direction. The penalty method is used for tangential behavior along with the coefficient of friction as 0.2, and the maximum shear stress is specified according to the load-slip curve. Studs defined as a master whereas concrete slab is defined as slave. Cohesive contact is used to simulate the behavior of adhesive material between concrete and CFRP, the values of normal and tangential stiffness are provided as input data. Reinforcement bars in both directions are defined as embedded region inside concrete.

2.2.4 Load and boundary conditions

The concentrated loading (Figure. 1) is modelled as an equivalent pressure load on the top surface of a 50 mm steel plate mounted top to the concrete slab. Dynamic explicit load control model is used in this study. Two roller and pin supports are used as a line restrains at mid of bearing plates that fixed at the bottom surface of steel section.

3 FINITE ELEMENT REULTS

The FE model is used to clarify the effect of bonding different thicknesses of CFRP top of concrete slab at the negative moment region on the ultimate capacity of girder. In this section, effect of CFRP on behavior of composite girder, mode of failure, and concrete-steel slip are investigated.

3.1 Validation of results

The FE results are validated with experimental results carried out for the same project (IN121053). Load-deflection curve is used to validate the numerical results as shown in Figure 6. The model showed good agreement and capability to predict the behavior of all parts of composite girders including concrete, steel, CFRP, and shear studs.

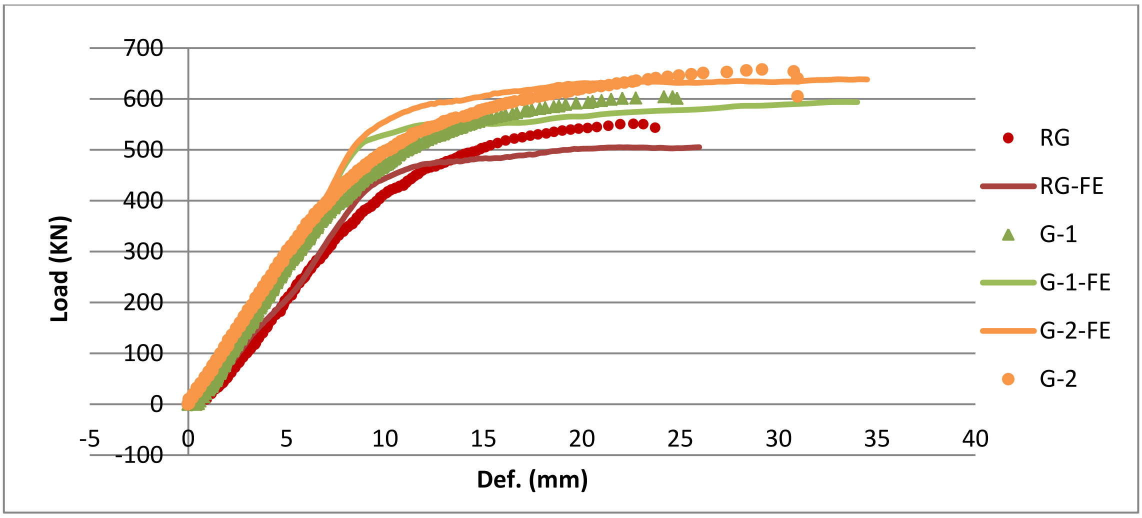


Figure 6. Numerical and Experimental load-deflection curves

3.2 *Ultimate capacity of composite girders*

The FE results for composite girders with different CFRP thicknesses are compared with girder RG as shown in Figure 7. The bond of CFRP to top of concrete slab improves strength and stiffness of girders G-1 to G-3 as compared to RG. The stiffness improvement of the girders is directly proportional to CFRP thickness. The ultimate capacity and ductility of girders bonded with different thicknesses of CFRP is directly proportional to CFRP thickness up to certain thickness where it started to decrease. FE results showed that the stress in CFRP is decreased as thickness of CFRP is increased. However, the total CFRP force is increased except for G-3 where CFRP force is less that G-2.

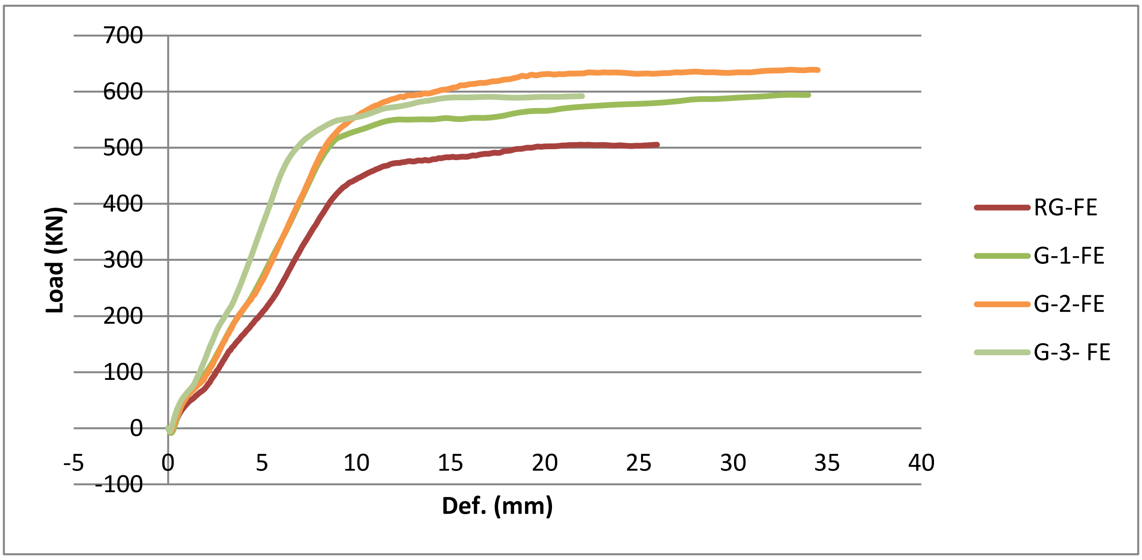
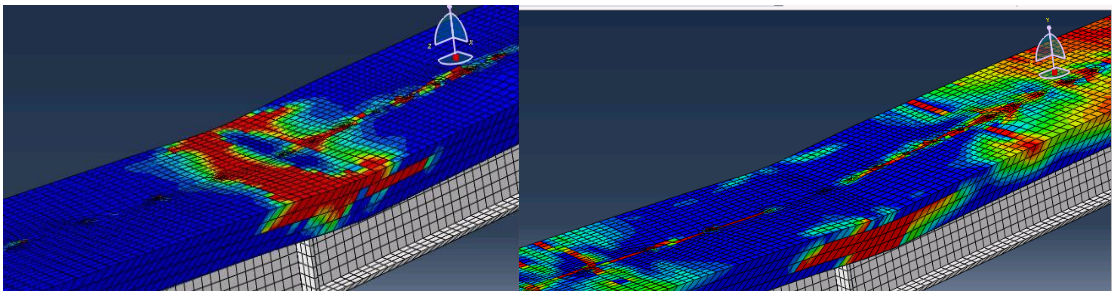


Figure 7. Numerical Load-deflection curves of girders

3.3 *Failure mechanism and mode of failure*

The concrete damage model showed that concrete slab at the negative moment region started to crack at a load of 145 KN for RG whereas this load in increased significantly for girders G-1, G-2, and G-3. The cracking load of G-3 is double that of RG. After cracking of concrete slab, the steel section started to yield at mid-span followed by yielding of steel section over the interior support before reaching the failure load. FE model showed that shear-compression failure mode controls the failure load of all girders. The concrete slab at mid-span has not reached crushing stress because of this type of failure. Compression and tension damage views of concrete slab at mid-span are shown in Figure 8a & 8b to illustrate the shear-compression failure.



a. Compression damage b. Tension damage

Figure 8. Concrete damage at mid-span

3.4 *Concrete-steel slip*

Contact model is used to model concrete-steel interface. This interface element gives the model an ability to figure out effect of shear studs on composite concrete-steel girder. The numerical results showed relative slip between bottom of concrete slab and top of steel beam. This slip is higher at mid-span compare to over the interior support because of higher tangential shear force and more spacing of shear studs. The use of CFRP top of concrete slab increased the slip over the interior support. At mid-span, no change in the relative slip is observed except close to ultimate load since girders started to reach higher load by use of CFRP which increased the tangential shear load on shear studs.

4 CONCLUSION

Three dimensional finite element model of continuous composite girder partially reinforced with CFRP at the negative moment region is developed. The FE results demonstrate that use of CFRP bonded to the top of concrete slab at the negative moment region increases the ultimate capacity and stiffness of girders. The increase of capacity is directly proportional to the thickness of CFRP up to certain thickness. The use of CFRP has a great advantage of maintaining the composite action between concrete and steel to higher level of loading without concrete cracking. The FE model is used to figure out relative slip between concrete and steel. The relative slip increased over the interior support by use of CFRP top to the concrete slab in that region.

5 ACKNOLEDGEMENT

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