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EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF FRP-REINFORCED BRIDGE DECK SLABS

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Abstract: Durability of concrete bridge deck slabs in harsh environments is a major concern. Corrosion of steel reinforcement due to de-icing salt is a common problem that led many researchers to use different types of non-corrosive rebars. The use of Fiber Reinforced Polymer bars (FRP) was considered as a design alternative due to their corrosion free behaviour and their high strength to weight ratio, especially for short span bridges. This paper presents comparison of the results of the Finite Element Modelling (FEM) of FRP reinforced concrete bridge deck slabs with restrained edges under concentrated static loads versus experimental test results. The FEM includes the test setup which represents the bridge structure and thus, there was no need to calibrate the slab restraint edge stiffness in the FE model from the experimental results, which is the common way. Hence, the FE model can be run before experiments and gives the opportunity to simulate different tests, varying different parameters in a very short time of comparison. Results show that FE modelling of the FRP reinforced slab including the supporting girders gives very close values in term of ultimate load, stress in FRP bars, deflection and failure mode when compared with experimental results.

1 INTRODUCTION

The significant development of infrastructure networks has made the cost of maintenance an important parameter to be taken into consideration in the design phase due to corrosion of steel reinforcement in concrete structures. As a result of this problem, in the last few decades a considerable amount of North America's transportation infrastructure is in need of repair or replacement (Yunovich et al.). The American Society of Civil Engineers (ASCE) estimates that over $1.6 trillion would be needed in the next five years in the U.S. to alleviate potential problems with civil infrastructure. Canada's deficit for its municipal infrastructure, which represents 70 percent of the country's total infrastructure was estimated to be $60 billion in 2004, and is expected to grow by $2 billion dollars per year (ISIS Canada 2007).

Generally, in bridge systems, concrete bridge decks deteriorate faster than any other bridge component due to direct exposure to environment, de-icing salts and ever-increasing traffic loads. To improve the durability of these structures, a new technique using composite materials, first as an external reinforcement and then as an internal reinforcement, have emerged during the last two decades. In fact the mechanical and physical properties of Composite materials, such as the high specific resistance (strength / weight ratio), non-corrodibility and ease of implementation have led to their growing interest. Composite materials also known as FRP (Fiber Reinforced Polymers) are made up of, as their name suggests fibers (carbon, glass or aramid) embedded in a polymer matrix (epoxy, polyester or vinylester), the fibers give the resistance to FRP and the resin guarantees the orientation of the fibers, their chemical protection as well as the distribution of the forces.

As a first step in this paper, finite element modeling of a Glass Fiber Reinforced Polymers (GFRP) reinforced concrete slab tested in laboratory is presented with the setup. The FEM and experimental results are then compared. Once this validation step has been fulfilled, a finite element parametric study can be launched to verify the effect of different parameters on the slab behaviour.

2 EXPERIMENTAL TESTING

2.1 Test setup and Slab configuration

The test setup and the slab to be modeled (Figure 1) represents a real-scale concrete deck slab reinforced with glass-FRP bars supported by two steel girders. The unidirectional slab is partially fixed to the steel beams with steel bolts instead of shear studs, the beams are supported by two parallel steel girders. Lateral stability is ensured by X bracings located at both ends of the beams. The use of the deck on only two girders is due to the limitation of space in the laboratory. The test setup was used in the first by El-Gamal S. During his Ph.D experimental tests (El-Gamal 2005).
The slab bottom transverse GFRP reinforcement ratio was 1.2% (#5 (15.9 mm) bars@ 115 mm) while in all other directions it was set to 50% of the main reinforcement ratio, which yield a reinforcement ratio of 0.6% (#5 bars @ 230 mm). This configuration represents a composite deck designed in accordance with chapter 16 of the Canadian Highway Bridge Design Code (CHBDC) (CAN/CSA-S6 2006).

This slab was tested up to failure under monotonic single concentrated load acting on the center of each slab over a contact area of 600 x 250 mm to simulate the footprint of sustained truck wheel load (87.5 kN CL-625 truck) (Bouguerra et al. 2011).

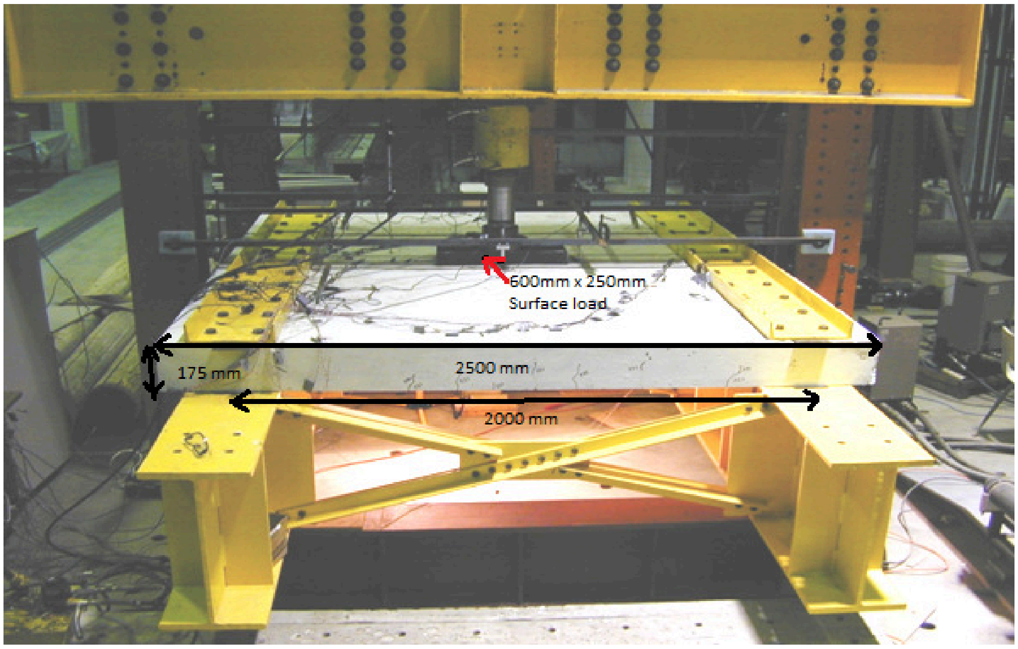

Figure 1 : Experimental test setup

2.2 Material proprieties

The concrete used in the experimental slab has 35 MPa compressive strength while the #5 (15.9mm)-Glass Fiber Reinforced Polymer (GFRP) reinforcing bars have an elasticity modulus of 42 GPa and an ultimate tensile strength of 778 MPa.

During the test, the bars strain was measured with electrical strain gauges installed on different locations. Deflection was monitored with LVDTs installed at the bottom and the top of the slab.

3 FINITE ELEMENT MODELING

The finite element model presented in this paper reproduces the whole experimental test setup. Modeling the test setup increased the mesh complexity which in return increased the computation time. A faithful modeling of the setup requires the use of linear elements (truss elements and rebars) as well as three-dimensional elements (27 nodes 3D solid element see Figure 2). Those elements were used to model six different groups of elements which are: the steel support beams; the concrete slab; steel channels that are connected to the bolts to provide edge restrain to the slab; the X- bracing; the steel bolts (shear studs) and the reinforcement rebars.

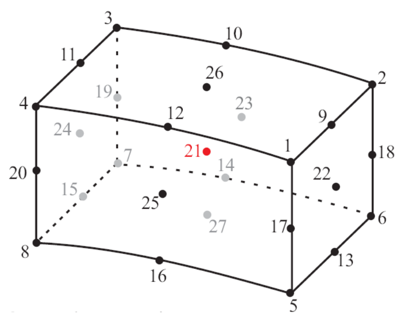

Figure 2 : 27 nodes 3D solid element

To reproduce the experimental tested slab, the concrete proprieties used in the FEM Slab are given in the table 1.

Table 1 : FEM Slabs concrete proprieties

f'_c (MPa)	f'_{cu} (MPa)	f_{cr} (MPa)	E (GPa)	ε_c	ε_{cu}
35	28	2.9	26.5	0.002	0.0035

The #5 (15.9mm)-FRP reinforced bars used in the model has the same proprieties as in the experimental one (tensile strength f_{GFRP} = 734 MPa with a modulus of elasticity E_{GFRP} = 42 GPa).

Since the setup is completely symmetrical, we only need to model the quarter, which helps reducing analysis time. The model of the restrained edges bridge deck slab is shown in Figure 3. The FE model was done with ADINA 8.4 software (ADINA 2004).

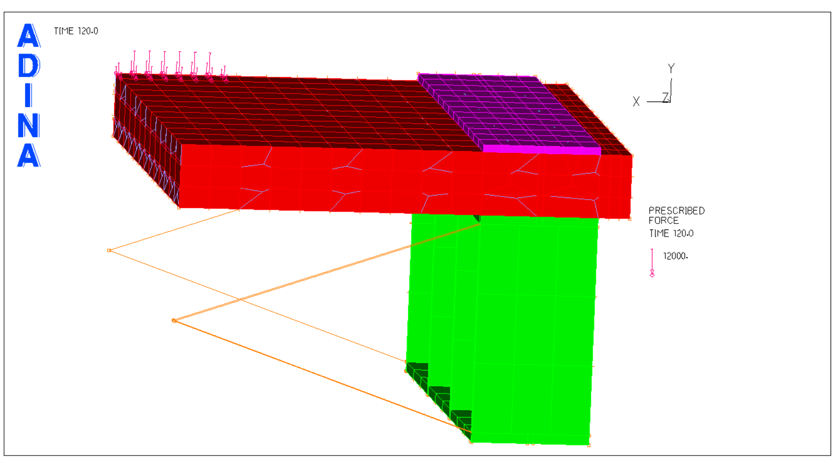

Figure 3 : Quarter modeled slab and test setup

Fixity conditions are a key step in the modeling as they directly affect the final results. The three-dimensional model uses "3D solid elements "and along the symmetry planes, only translations in the directions X, Y and Z were allowed. Therefore, two planes of symmetry were considered to model the quarter of the test setup requires:

- Symmetry according to the YZ plane: this plane is parallel to the beams axis and intersects the slab in 2, as well as the braces at their junction. All the elements in contact with this plane will be free to move (translation) in Y and Z directions, while their translation along X will be prevented (see Figure 4).
- Symmetry according to the XY plane: this plane intersects the slab as well as the steel beams and the channel. All the elements in contact with this plane will be free to move (translation) according to the directions Y and X, while their translation along Z will be prevented (see Figure 4).

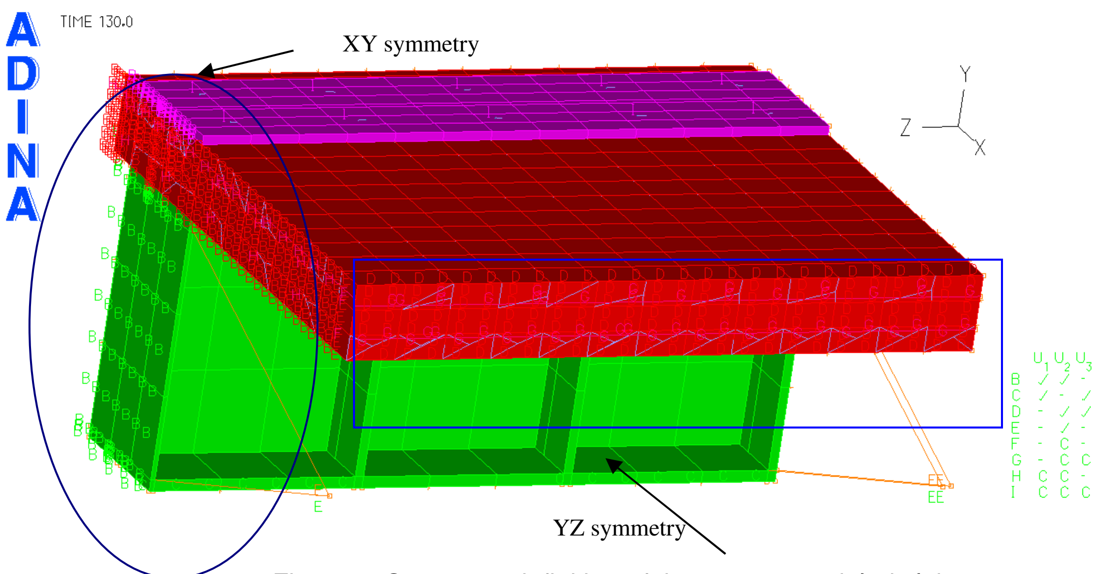

Figure 4: Symmetry definition of the quarter modeled slab

The applied load at the center of the slab (87.5 kN) was cut in four by the two planes of symmetry and its actual dimensions are 300 mm x 125 mm; this load was distributed on 24 nodes.

4 COMPARISON BETWEEN THE FEM RESULTS AND EXPERIMENTAL FINDINGS

4.1 Load deflection relationship

The load-deflection results from the FE model are compared with those from the experimental tests; the two diagrams are shown in Figure 5.

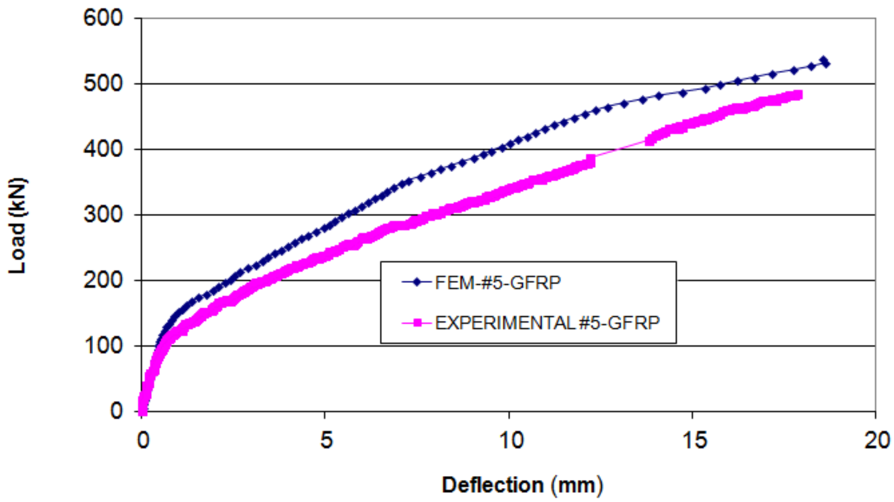

Figure 5 : Load-deflection behaviour-Comparison between FEM and experimental slabs reinforced with #5-GFRP bars

Figure 5 shows that the experimental slab failure load is 483 kN corresponding to a deflection of 17.9 mm. On the other hand, the FE model gives an ultimate load of 532 kN and a deflection of 18.6 mm. It can be seen that the difference between the finite element model and the experimental test is acceptable (10% and 4% for load and deflection respectively).

The overall load-deflection behaviour is similar for both experimental and FE model and is divided into two different phases with a transition phase in between:

- Phase 1: the behaviour of the slab is governed by the behaviour of non-cracked concrete. This phase is independent from the proprieties of the reinforcing bars. One can see that the experimental and FEM curves are perfectly superimposed;
- Phase 2: after the cracking of the concrete, the behaviour of the slab is governed by the properties of the reinforcing bars (GFRP), so the slope of this curve depends on the axial stiffness of the bars.

Now that the modeling results are fairly close to the experimental ones, we can vary reinforcement type to see their effect on the slab behaviour. The same slab was modeled with #5 CFRP bars instead of #5-GFRP. The CFRP bars has a tensile strength f_{CFRP} = 1240 MPa with a modulus of elasticity E_{CFRP} = 145 GPa.

The comparison of the load-deflection behaviour of the two FE models with GFRP and CFRP reinforcement bars is given in Figure 6.

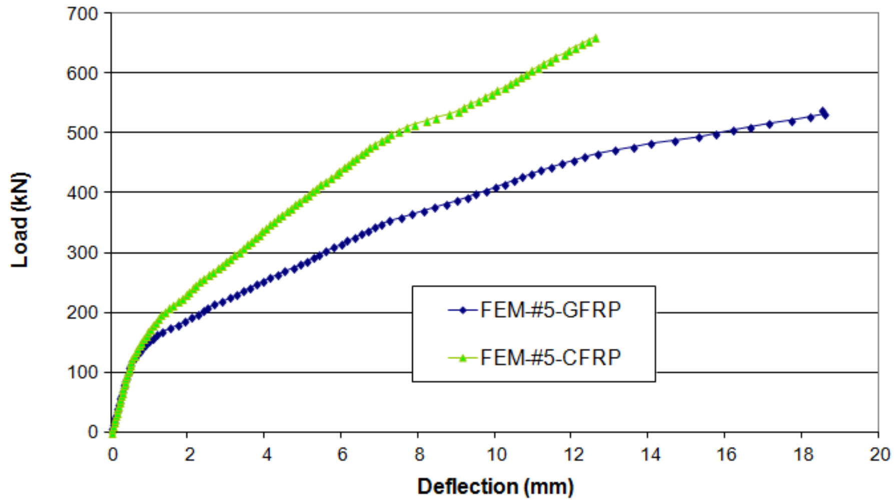

Figure 6 : Load-deflection behaviour - Comparison between FEM slabs reinforced with #5-GFRP and #5-CFRP bars

The shape of the load deflection curve of the CFRP reinforced slab is similar to the GFRP one. In the first phase, the two curves are superimposed, and then in the second one, the slope is higher for the CFRP reinforced slab. This difference is due to the CFRP modulus which is 3 times higher than the GFRP one. The CFRP reinforced slab ultimate strength is higher while the deflection is lower compared to the GFRP reinforced slab and this is because of the difference in modulus of elasticity and the axial stiffness.
The results are summarized in Table 2.

Table 2 : Comparison of the results of two reinforced slabs with #5 (15.9 mm)-CFRP and #5 (15.9 mm)-GFRP bars

	Ultimate Load (kN)	Ultimate Deflection (mm)
GFRP	532	18.6
CFRP	660	12.6
Comparison	+24%	-32%

To investigate the effect of bar diameter, a #4(12.7 mm)-CFRP bars reinforced slab was modeled and analyzed. The results obtained are compared with those of the #5-CFRP reinforced slab in the Figure 7.

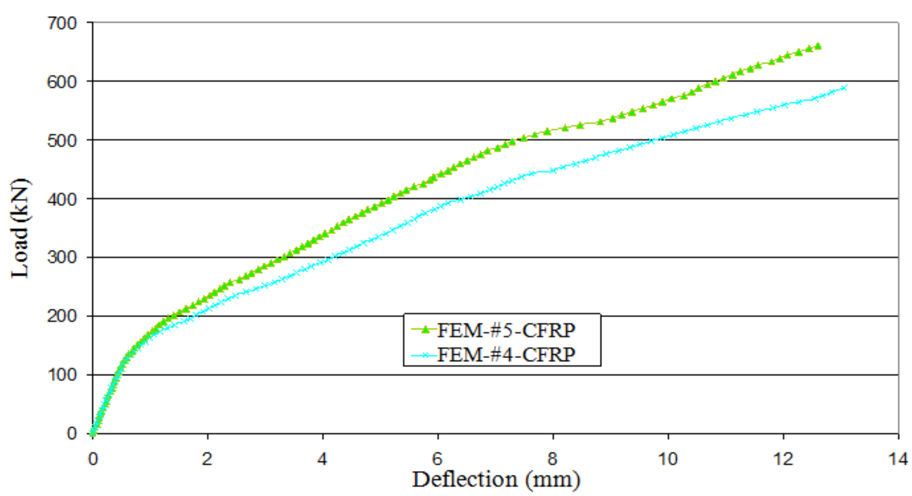

Figure 7 : Load-Deflection behaviour - Comparison between FEM slabs reinforced with #5-CFRP and #4-CFRP bars

Figure 7 shows that reducing the bar diameter and thus the axial stiffness reduces the slab ultimate strength as well as the slope of the second phase. The deflection of the #4 CFRP and #5 CFRP reinforced slabs is similar. These results are summarized in Table 3**.**

Table 3 : Comparison of the results of CFRP reinforced slabs with #5 and #4 bars

	Ultime Load(kN)	Ultime Deflection (mm)
#4-CFRP	588	13.1
#5-CFRP	660	12.6
Comparison	-11%	+4%

4.2 Failure mode

4.2.1 Lab GFRP reinforced tested slab

The failure mode of the slab tested in the laboratory reinforced with #5- GFRP bars was by punching under the applied load as shown in the **Erreur ! Source du renvoi introuvable.**.

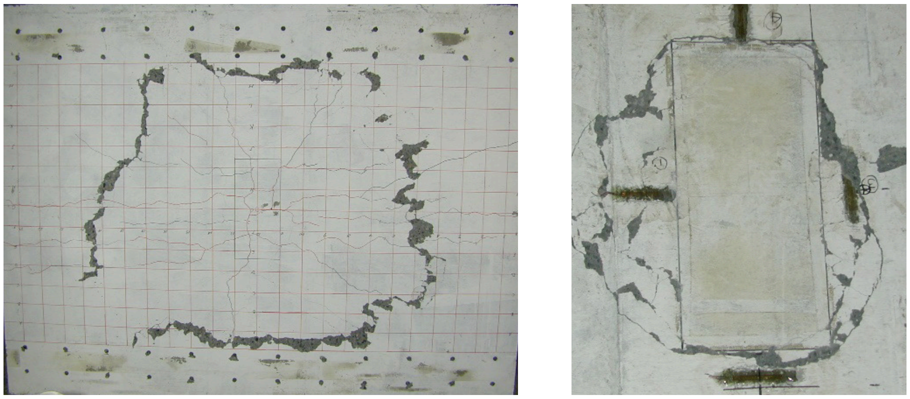

Figure 8: Failure mode of the laboratory tested slab

4.2.2 FE modeled #5-GFRP reinforced slab

The failure mode of the modeled GFRP reinforced slab is a combination of concrete crushing at the vicinity of the loading area and at the support location. Figure 9 shows the FEM modeled slab failure mode. The experimentally tested slab had a rubber layer between the concrete and the steel beam. This rubber allowed the rotation of the slab and reduced stress concentration, the fact that this rubber wasn't modeled for the FEM slab resulted in concrete crushing at the support due to stress concentration.

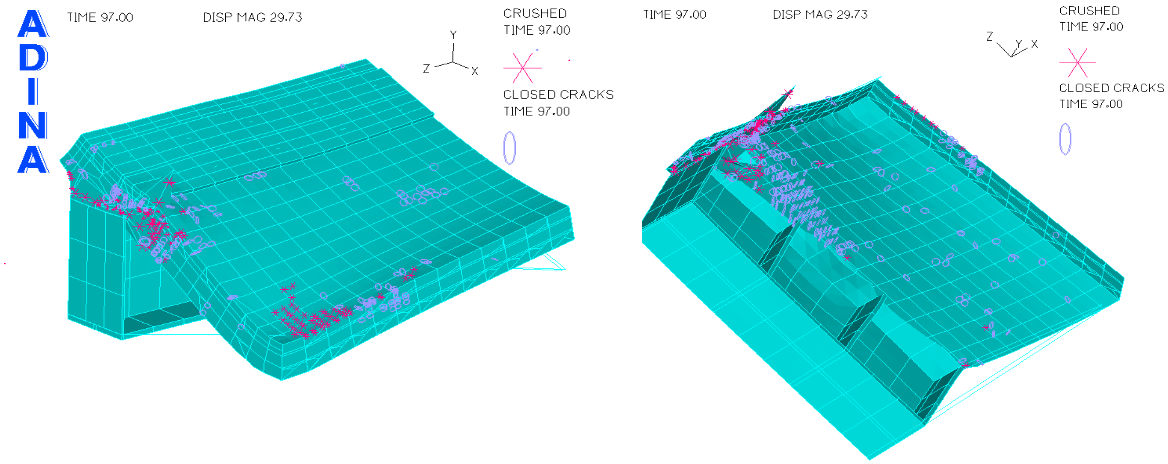

Figure 9: Failure mode of FEM #5-GFRP reinforced slab

4.2.3 FE modeled slab (CFRP reinforced)

The failure modes of the both FE modeled CFRP reinforced slabs (with #5 and #4 bars) are similar to failure mode of the FEM reinforced slab with #5- GFRP bars. Figure 10 shows a view from above and from below of the failure mode of the FEM #5-CFRP reinforced slab. As the FEM GFRP reinforced slab, we noticed concrete crushing at the supports which didn't happened for the experimentally tested slab.

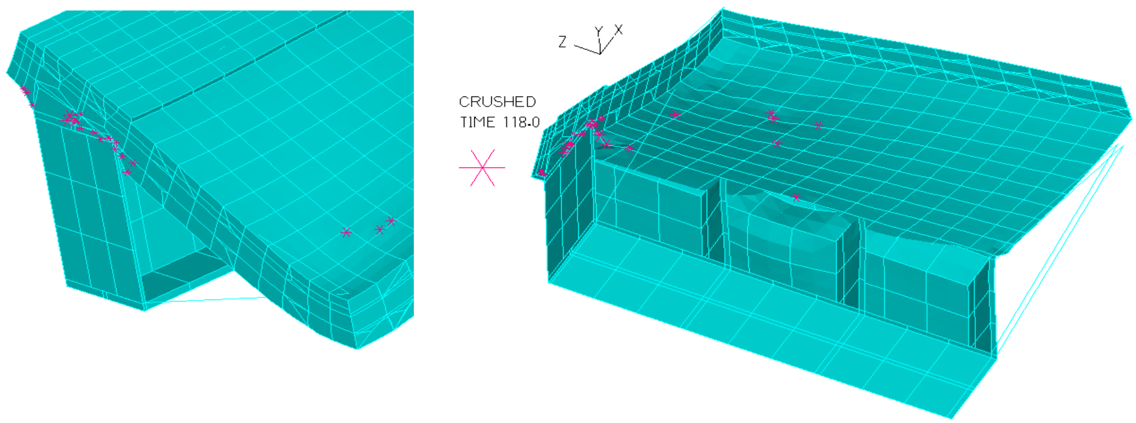

Figure 10: Failure Mode of the FEM #5-CRFP-reinforced slabs

As shown in Figure 11, all slabs modeled have better deflection load behavior. However, the curve of the slab having the GFRP bars as reinforcement is comparable to the slab tested in the laboratory until the failure. At the failure, the difference between the finite element model and the experimental test, for the last discussed slabs, is 10% and 4% for load and deflection respectively. On another side, FEM CFRP reinforced slab, at failure, shows 37 % and -30% for load and deflection respectively compared to the GFRP reinforced tested slab.

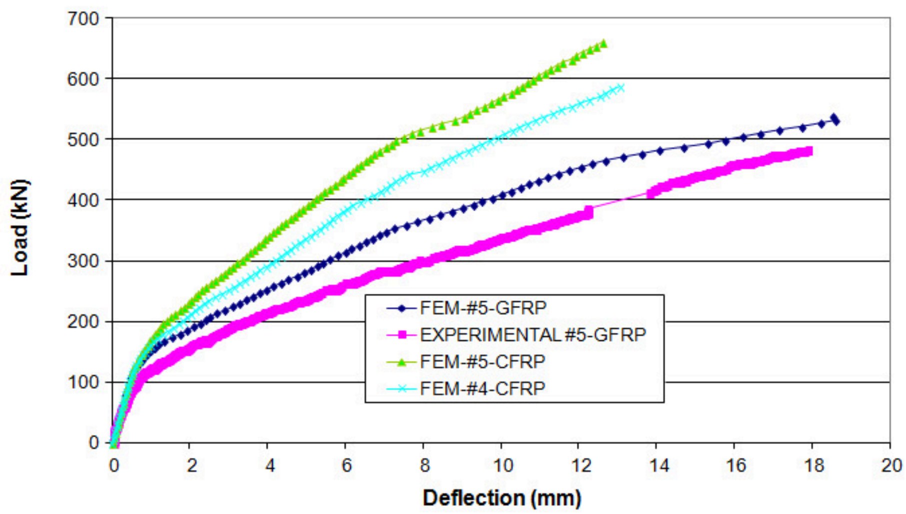

Figure 11: Load-Deflection behavior- Comparison of all the FEM and experimental slabs

5 CONCLUSIONS

This paper presents the results of Finite Element Modeling of a GFRP reinforced bridge deck slab with restrained edges. The model included the tested deck slab as well as the test setup. Usually, modeling this kind of decks involves the use of spring elements at the edge of the slab to simulate the restrain. The stiffness of the springs is calibrated from the experimental test results, which means that to study the effect of different parameters, one need to perform experimental tests first then use the results to calibrate the FE model and run simulations.

Using FEM software to model FRP reinforced bridge deck slab with restrained edges including the test setup (girders) prove to give pretty good results compared to the experimental testing in term of ultimate strength and deflection. The failure mode of the FE modeled slab was similar to the experimental one although we noticed concrete crushing at the supports which didn't happened for the experimentally tested slab. The reason of this difference in behaviour is due to the use of rubber layer between the concrete and the support in the laboratory setup, this rubber layer permitted the rotation of the slab as the loading increased. The rubber was absent in the FE model resulting in stress concentration as the support with the increase of deflection. The stress concentration at the support led to concrete crushing.

Acknowledgements

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