THE EUROPEAN PROJECT SUREBRIDGE
Analysis of laboratory test beams

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Summary

The European research project SUREBridge (Sustainable Refurbishment of Existing Bridges) is developing a new concept for the structural strengthening of road bridges: glass fibre-reinforced polymer (GFRP) sandwich panels are installed on top of the existing concrete slabs; pre-stressed carbon fibre-reinforced polymer (CFRP) laminates are adhesively bonded to the bottom of the longitudinal girders.

Laboratory tests were carried out on 6-m long beams subjected to four-point bending: one reference not strengthened concrete beam and three strengthened beams. Finite element models of the tested beams were developed by using the commercial software Straus7®. A fibre model with `BEAM` and `LAMINATE` elements was defined with specific non-linear stress-strain curves for the confined and unconfined concrete, steel reinforcements, GFRP, and CFRP. The theoretical load-deflection curves obtained through non-linear static analyses showed very good matching with the experimental results.

Keywords

fibre-reinforced polymers, structural strengthening, experimental testing

Introduction

The European research project SUREBridge [1] (Sustainable Refurbishment of Existing Bridges) is developing a new concept for the structural strengthening of road bridges. The target is to exploit the remaining capacity of the superstructure of concrete and steel-concrete bridges, preserving the structural elements of the deck (girders and slab) and increasing the load-carrying capacity to the desired level. This is achieved by using light-weight, tailor-made glass fibre-reinforced polymer (GFRP) sandwich panels [2], installed on top of the existing concrete slab, and carbon fibre-reinforced polymer (CFRP) laminates applied to the bottom side of the girders. CFRP laminates are pre-stressed using an innovative technique [3], which avoids stress peaks at the laminate ends, thus preventing early delamination. Furthermore, the GFRP panels can be manufactured either of the same width or wider than the existing deck, thus enabling to widen the road section if needed.

The effectiveness of the SUREBridge technique was proved through full-scale tests on T-shaped cross-section prototype beams. The tests had to be representative of the conditions occurring in real concrete bridges, since the T-shaped cross section represents a simplified version of a longitudinal girder with an upper collaborating slab. Finite element models based on the fibre-modelling approach were developed with the commercial software Straus7® [4]. The theoretical load-deflection curves obtained through non-linear static analyses closely matched the experimental results.

Experimental tests on prototype beams

Four specimens were designed to test the strengthening properties of the SUREBridge solution:

- Specimen 1: not strengthened reinforced concrete beam, used as reference;
- Specimen 2: prototype beam with transversal GFRP panels and pre-stressed CFRP laminate; GFRP-concrete bonding obtained with mortar, aggregates, and mechanical anchors;
- Specimen 3: prototype beam with longitudinal GFRP panels and pre-stressed CFRP laminate; GFRP-concrete bonding obtained with epoxy adhesive;
- Specimen 4: prototype beam with longitudinal GFRP panels and pre-stressed CFRP laminate; GFRP-concrete bonding obtained with mortar, aggregates, and mechanical anchors.

Figure 1a shows the cross section of the reference beam (specimen 1), while Figure 1b illustrates the same cross section strengthened with the SUREBridge technique (specimen 3). In what follows, the results of experimental tests and finite element analyses for such two cases will be illustrated.

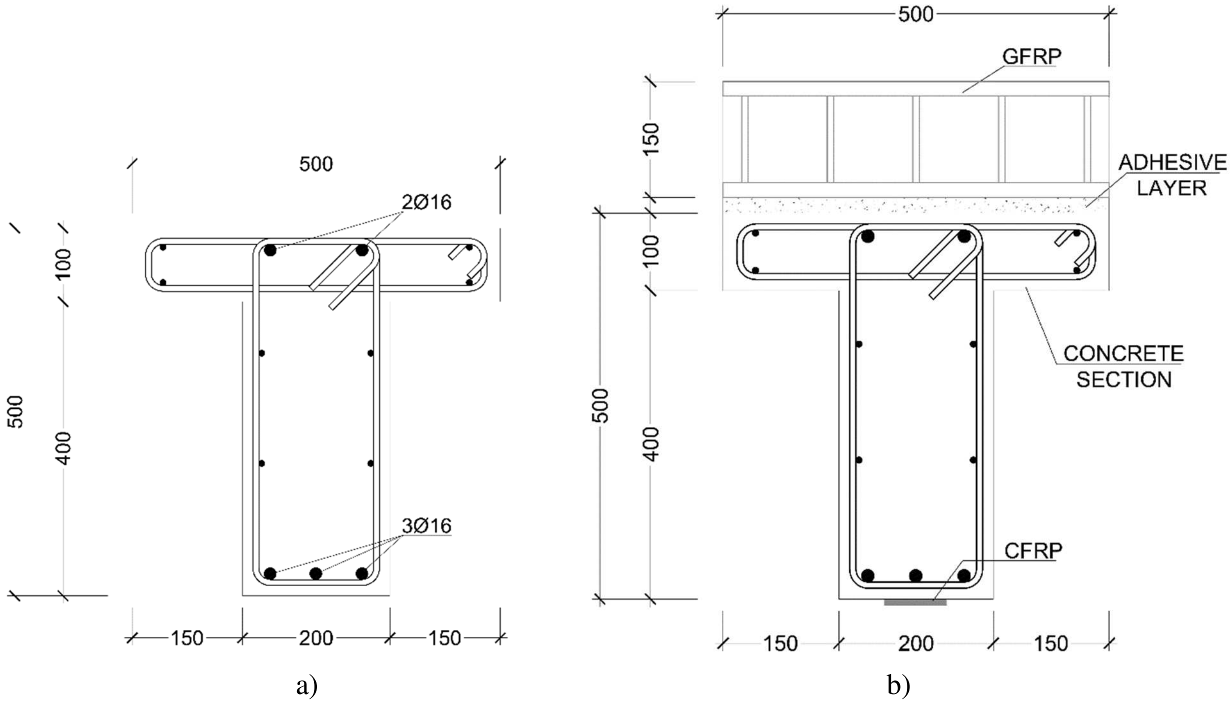


Figure 1: Prototype reinforced concrete beam: a) un-strengthened; b) strengthened

The concrete cross section of the prototype beams is composed of a top flange, 500 mm wide and 100 mm thick, and a web, 400 mm high and 200 mm wide. Thus, the total concrete section height will be 500 mm. The GFRP panels installed on top have a total height of 150 mm, while the CFRP laminates applied at the bottom have an 80 mm x 1.4 mm cross section. The detailed geometrical properties of the GFRP panels are summarised in Table 1.

The resisting bending moment of the strengthened composite section, M_{rd}, was evaluated by extending to the present case the normally accepted hypotheses for ultimate limit state (ULS) verifications of reinforced concrete elements (Section 6.1 of Eurocode 2 [5]):

- plane sections remain plane with no relative sliding between concrete and steel;
- the tensile strength of concrete is ignored;
- the stresses in concrete in compression are derived from the design stress-strain relationships given in Section 3.1.7 of Eurocode 2 [5] (here, a bilinear stress-strain relationship is used);
- elastic-plastic behaviour is assumed for steel reinforcements.

In addition to the above, further specific assumptions were made:

- the whole composite section remains plane after deformation with no relative sliding between CFRP/GFRP elements and concrete;
- both CFRP and GFRP are assumed to behave as elastic-brittle materials;
- delamination of CFRP/GFRP from concrete is not taken into account.

A calculation datasheet was used to implement the above-mentioned assumptions and to evaluate the ultimate bending moment of the specimens. Table 2 summarises the values of the ultimate bending moment, M_u, and the corresponding maximum expected test load, F.

Element	Property	Value
Skins	thickness (mm)	19.1
Webs (Flat)	thickness (mm)	8.5
	height (mm)	111.8
	spacing (mm)	102.4 + 8.5
Webs (Flute)	thickness (mm)	1.12
	height (mm)	111.8
	spacing (mm)	70.0 + 1.12

Table 1: GFRP panels geometrical properties

Specimen	Description	Ultimate bending moment M_u (kNm)	Ultimate test load F (kN)
1	Reinforced concrete reference beam	139	126
3	Longitudinal GFRP + pre-stressed CFRP	418	380

Table 2: Ultimate bending moment and test loads

In July 2017, the 6-m long prototype beams with the described cross sections were tested under four-point bending (Figure 2 and Figure 3) in the laboratory of the Structural Engineering Division of the Department of Civil and Environmental Engineering at Chalmers University of Technology (CTH).

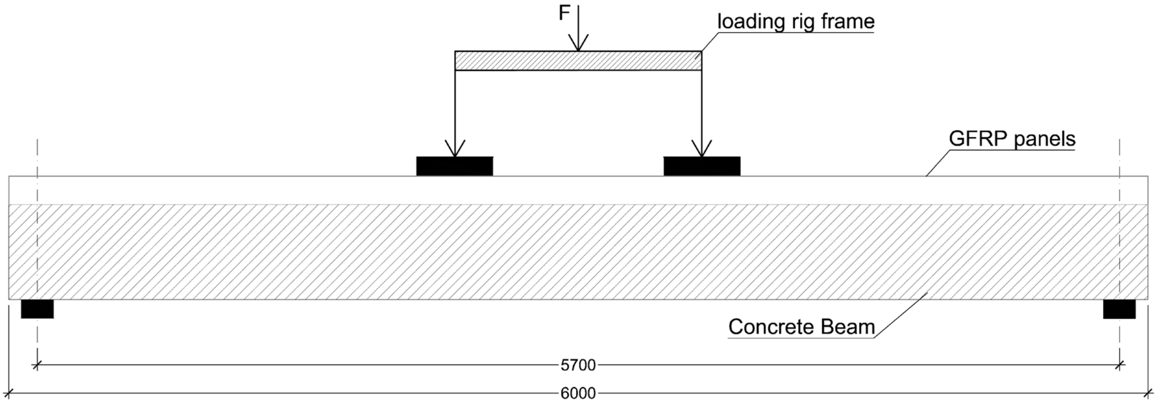
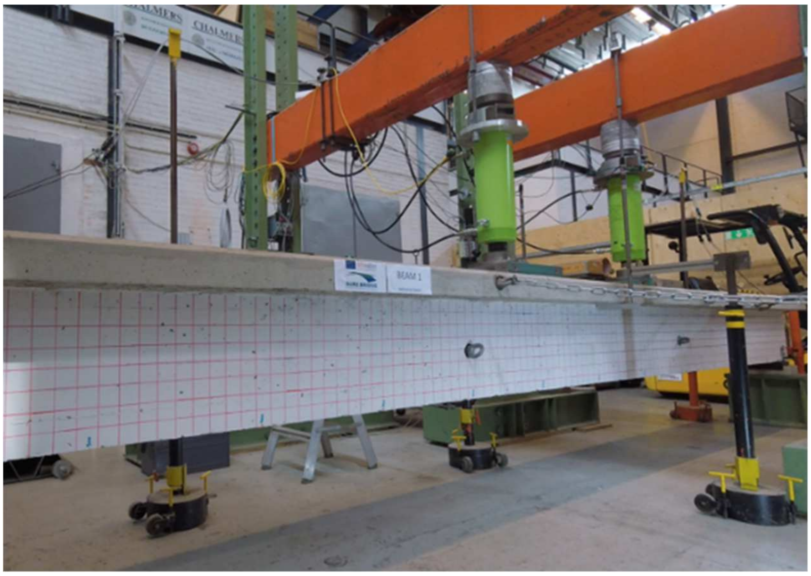
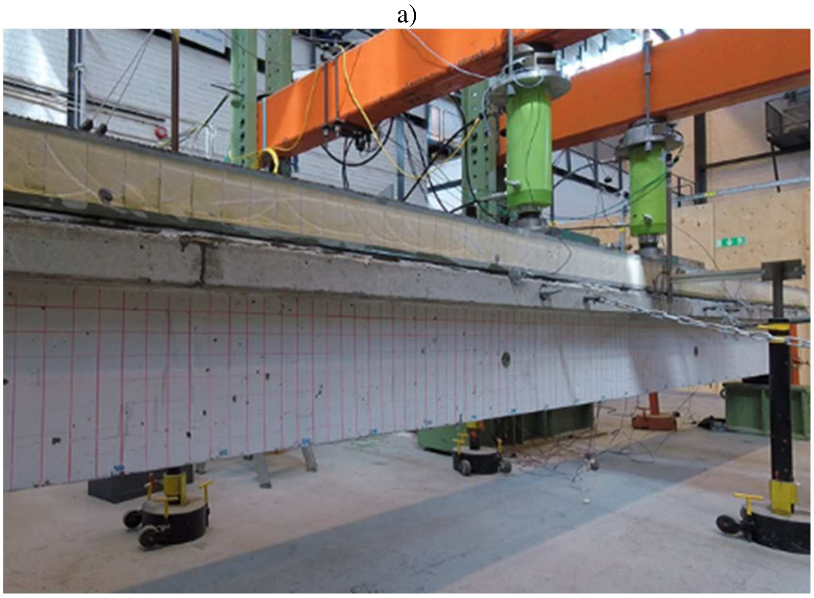


Figure 2: Four-point bending test configuration



a)



b)

Figure 3: Four-point bending test on a) specimen 1; b) specimen 3

Finite element analysis of prototype beams

Calibration of the finite element model for non-linear analysis

In order to have a theoretical prediction of the structural behaviour of the prototype beams, in particular the expected failure load and corresponding deflection at mid-span, finite element non-linear analyses were carried out. The finite element models were calibrated referring to the experimental results obtained during some preliminary laboratory tests on rectangular cross-section beams. Such tests were conducted at CTH in October 2016. Three models were analysed by using the commercial FEM software Straus7® [4], each corresponding to one of the tested beams:

- Beam 1: not strengthened concrete beam, used for reference (Figure 4a);
- Beam 2: concrete beam with passive CFRP laminates on the bottom side (Figure 4b);
- Beam 3: concrete beam with pre-stressed CFRP laminates on the bottom side (Figure 4c);

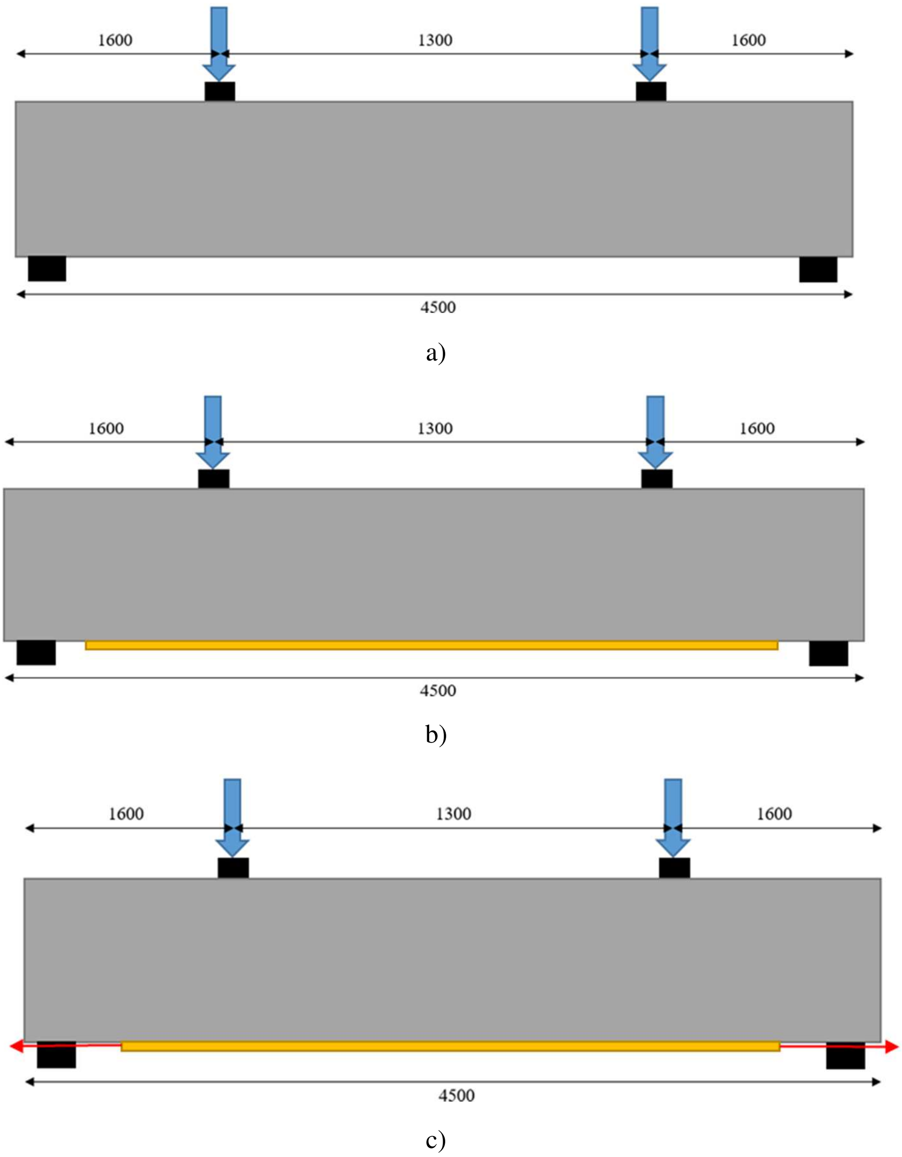
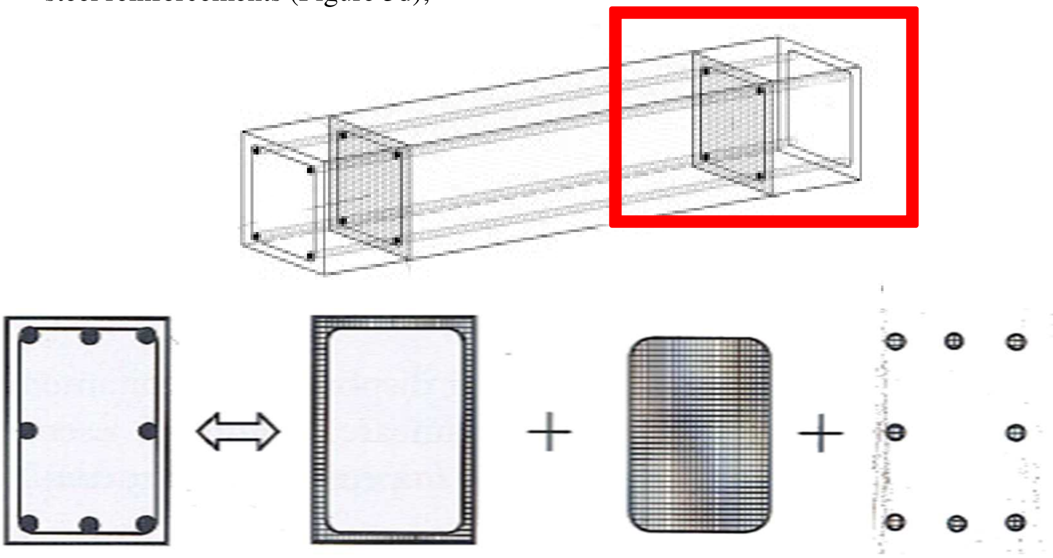


Figure 4: a) Beam 1; b) Beam 2; c) Beam 3

The finite element models were defined by using `BEAM` elements for both concrete and reinforcement steel. A fibre-modelling approach was used, whereas the tested beam is represented as the assemblage of small `BEAM` elements representing ideal longitudinal fibres. This approach is often used to represent the non-linear behaviour of reinforced concrete structural members in seismic analyses. Figure 5a shows the cross section of the beam composed of three different parts, each corresponding to a different material with specific mechanical properties and stress-strain curves:

- unconfined concrete: lateral deformations of the material are not constrained (Figure 5b);
- confined concrete: lateral deformations of the material are constrained by means of transversal steel reinforcements (stirrups or hoops), with a resulting higher strength and ductility (Figure 5c);
- steel reinforcements (Figure 5d);



a) b) c) d)

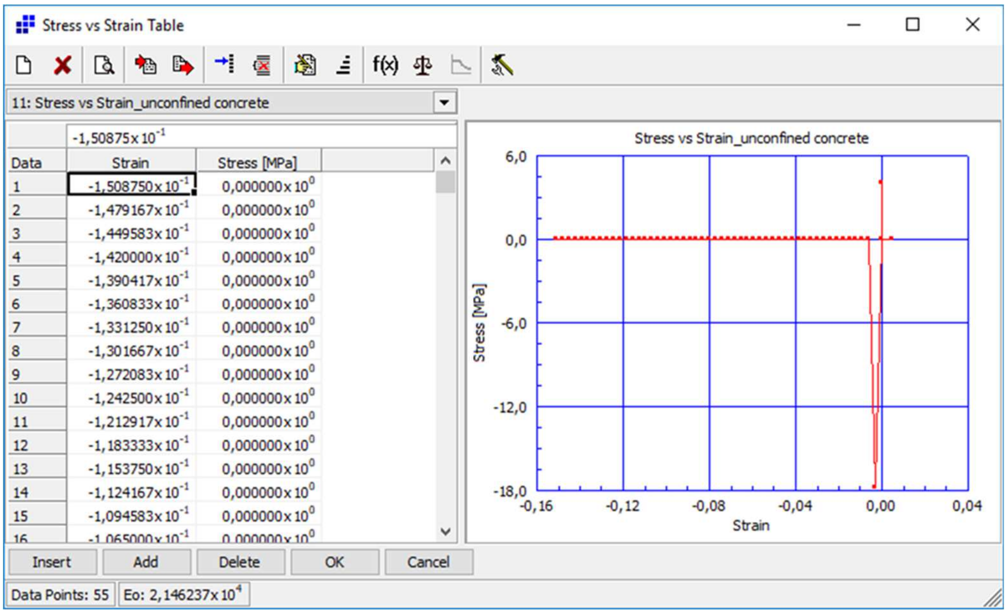
Figure 5: a) Concrete section; b) Unconfined concrete; c) Confined concrete; d) Steel reinforcements

The modified model by Kent and Park [6] was used to define the stress-strain curves for confined and unconfined concrete in compression. Instead, the stress-strain curves both for confined and unconfined concrete in tension were extrapolated from the values of the elastic modulus and mean tensile strength (Figure 6). An elastic-plastic stress-strain curve was chosen for the steel reinforcements (Figure 7), while an elastic-brittle stress-strain curve was considered for the CFRP laminates (Figure 8).

The CFRP laminates were connected to the bottom of the concrete beam using an epoxy adhesive layer. This layer was schematised as a continuous distribution of springs and introduced into the finite element model by using `CONNECTION` elements. The equivalent shear and axial stiffness of such elements were computed based on the thickness of the adhesive layer and the values of its elastic moduli given by the producer.

Furthermore, the pre-stress distribution on the CFRP laminates of beam 1 was obtained from the strain values measured with the strain gauges during the laboratory tests performed at CTH (Figure 9).

The cross sections of the finite element models for beams 1, 2, and 3 are presented in Figure 10. Furthermore, a detail of the connection between the CFRP laminates and the concrete beam is shown in Figure 11. The non-linear analysis of the FE models was developed with progressive and appropriate load increments to obtain the theoretical load-deflection curves presented in Figure 12, Figure 13, and Figure 14 for beams 1, 2, and 3, respectively. In the same figures, the results of the experimental tests are shown for comparison. The points corresponding to the failure of concrete, steel, and CFRP are clearly recognisable.



a)

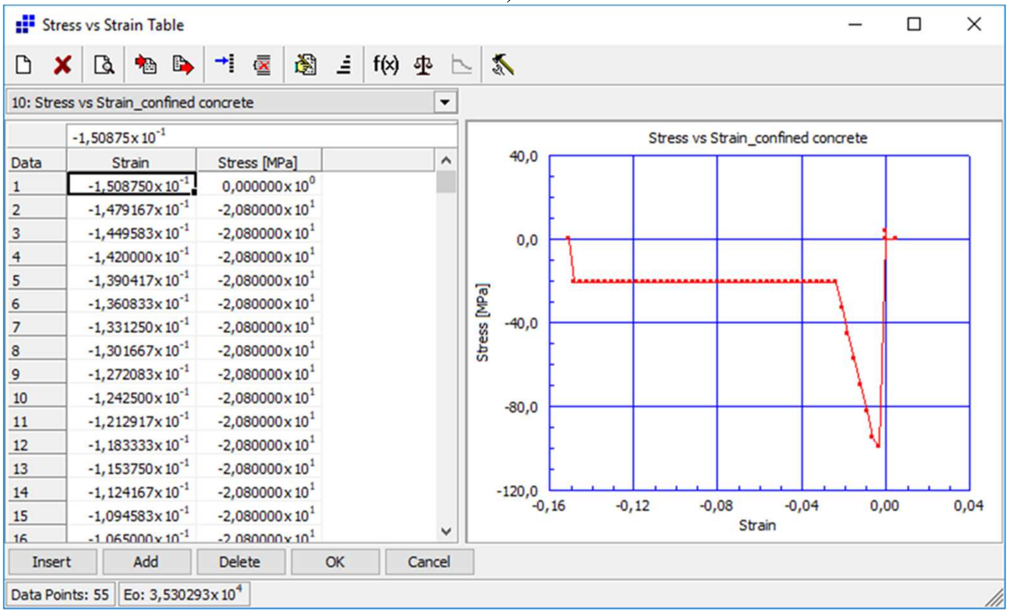


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Figure 6: Stress-strain curves for: a) Unconfined concrete; b) Confined concrete

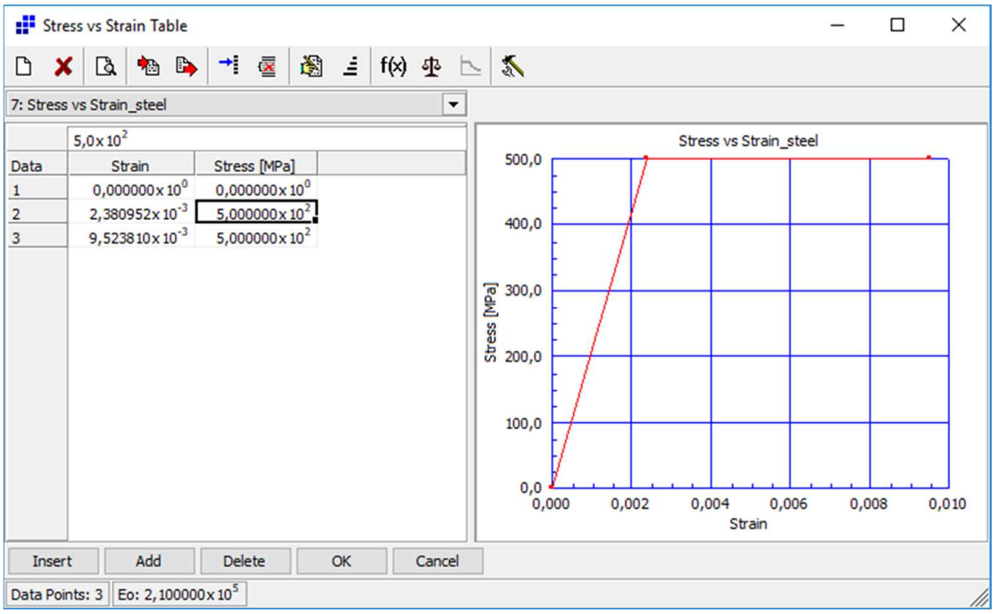

Figure 7: Stress-strain curve for steel

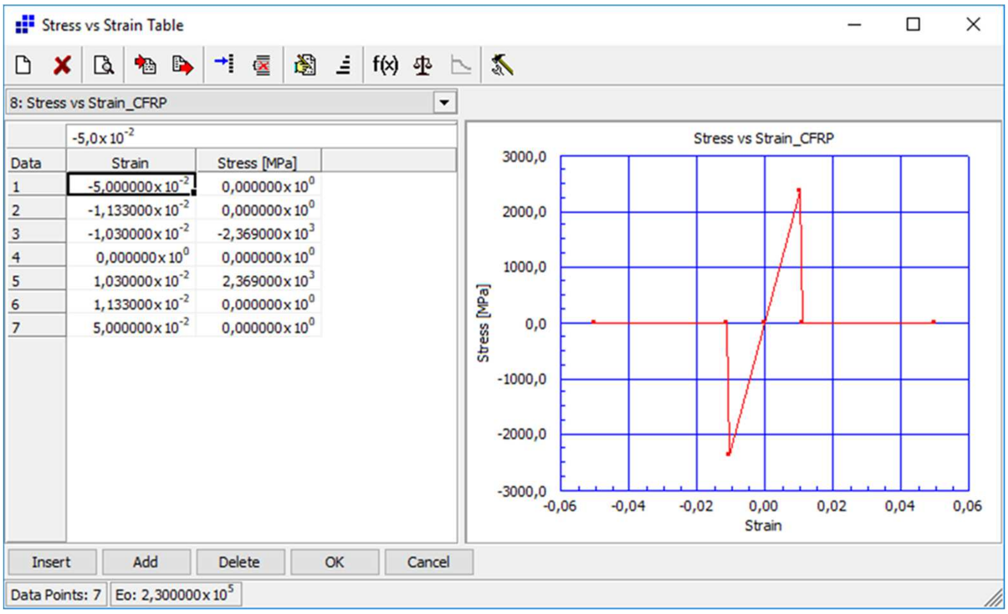

Figure 8: Stress-strain curve for CFRP laminates

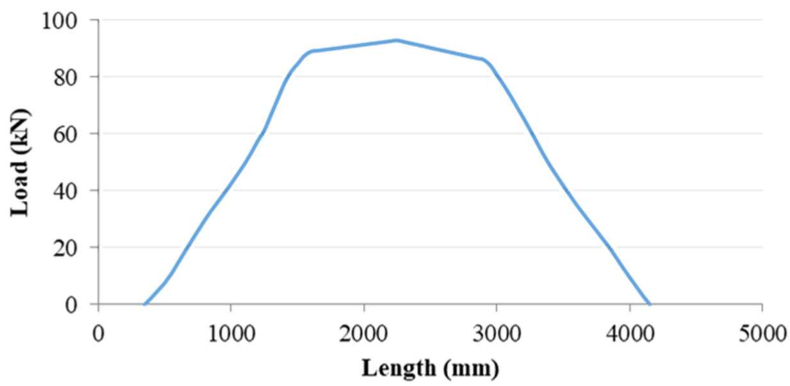

Figure 9: Pre-stress distribution for CFRP laminates

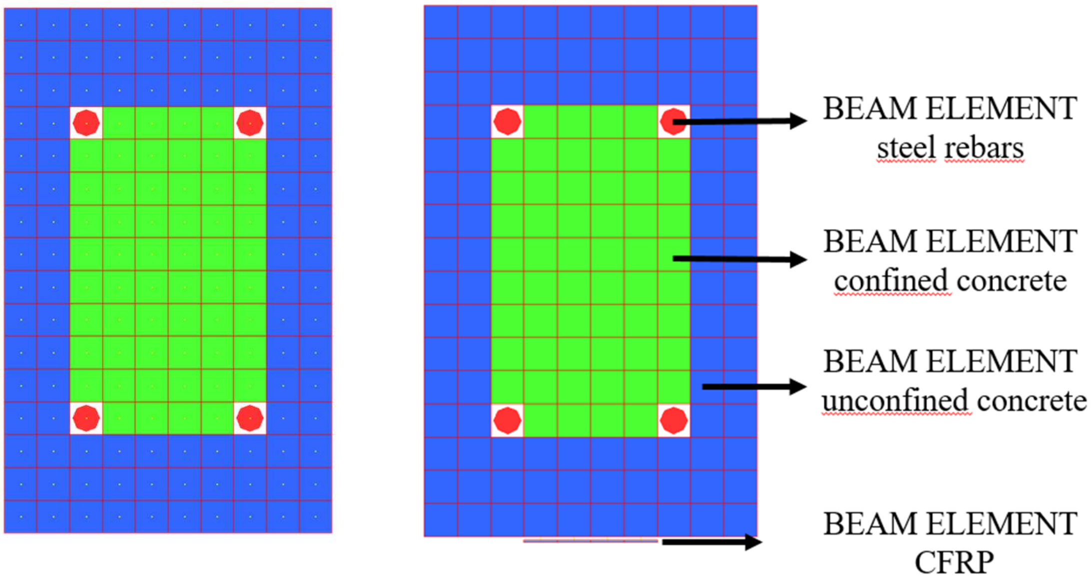

Figure 10: FE models for a) beam 1; b) beam 2

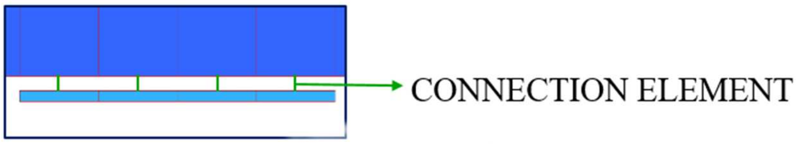

Figure 11: Connection between CFRP laminates and concrete

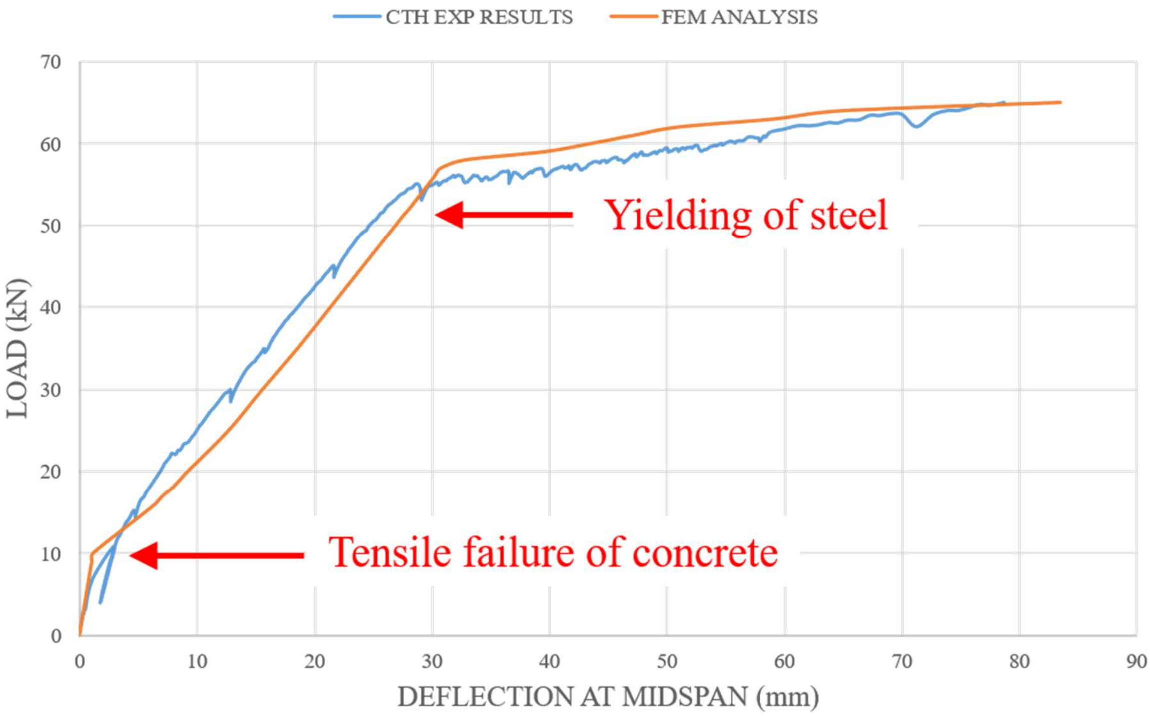

Figure 12: Comparison between the theoretical and the experimental load-deflection curves – Beam 1

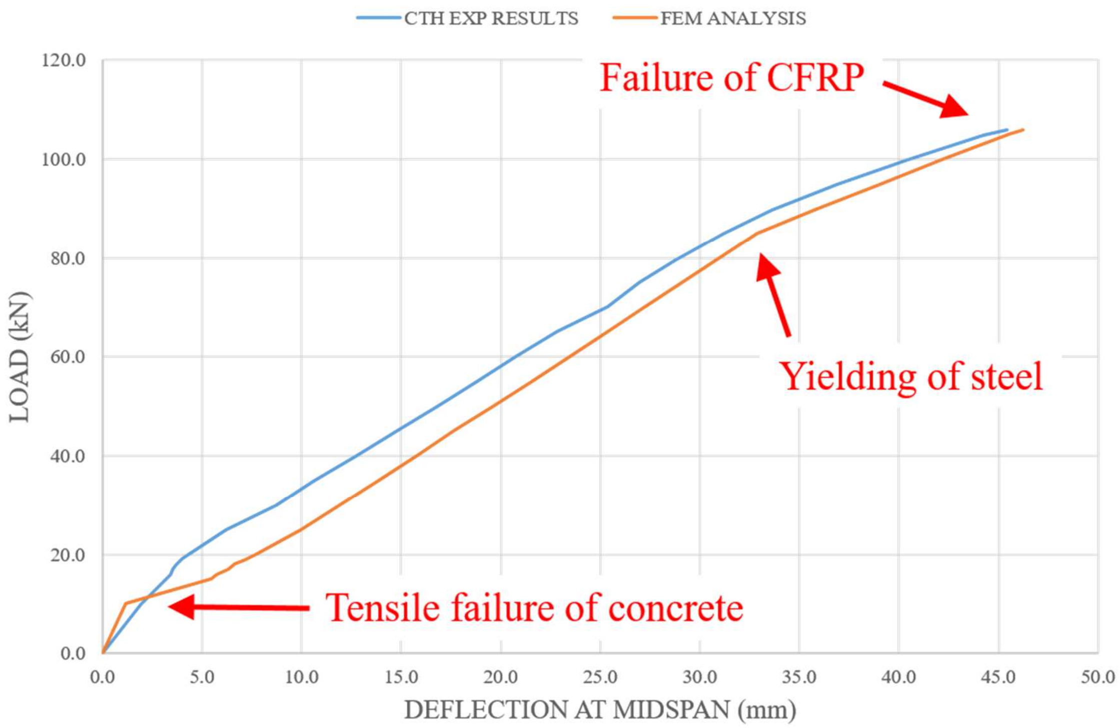

Figure 13: Comparison between the theoretical and the experimental load-deflection curves – Beam 2

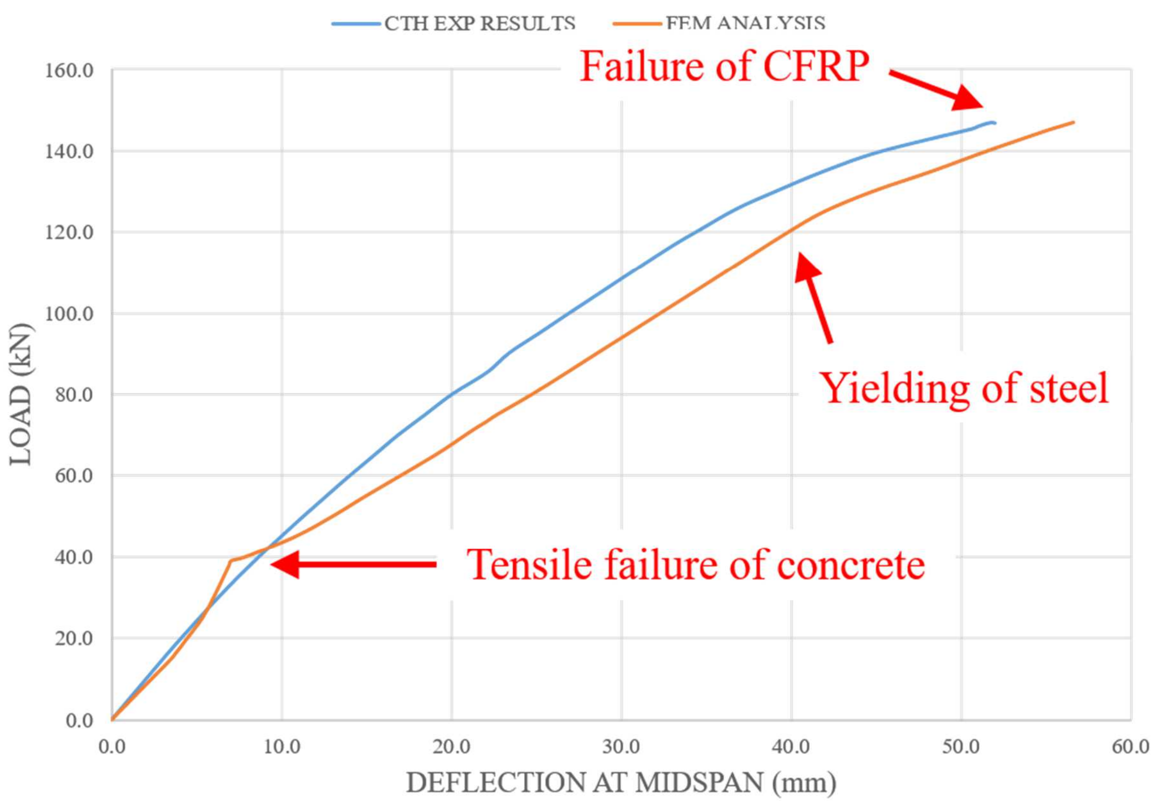

Figure 14: Comparison between the theoretical and the experimental load-deflection curves – Beam 3

Non-linear analysis of the prototype beams

The modelling of the beams tested at CTH in October 2016 was useful to set up the most effective modelling approach and to calibrate some of the analysis parameters, in particular the stress-strain curves. Next, finite element analysis with fibre elements was developed also for the prototype beams. The cross sections of specimen beams 1 and 2, along with the corresponding finite element representations are illustrated in Figure 15 and Figure 16, respectively.

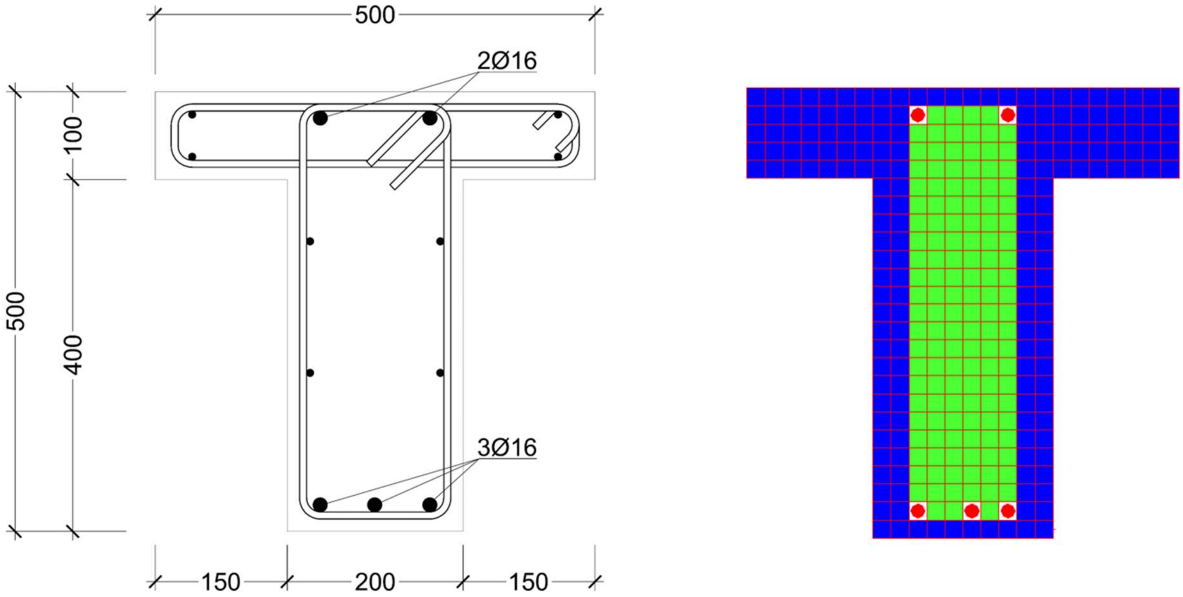

Figure 15: FE cross section of specimen 1

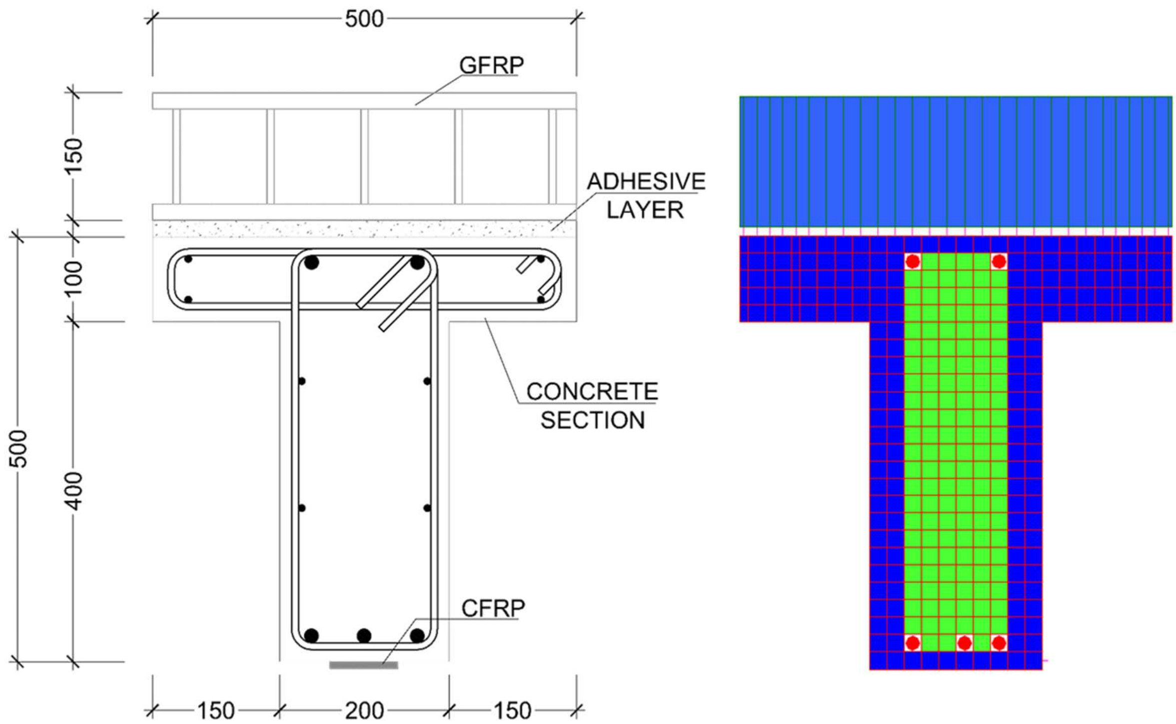

Figure 16: FE cross section of specimen 2

Figure 17 shows the stress-strain curves for unconfined and confined concrete. Figure 18 and Figure 19 show the stress-strain curves for steel and CFRP, respectively.

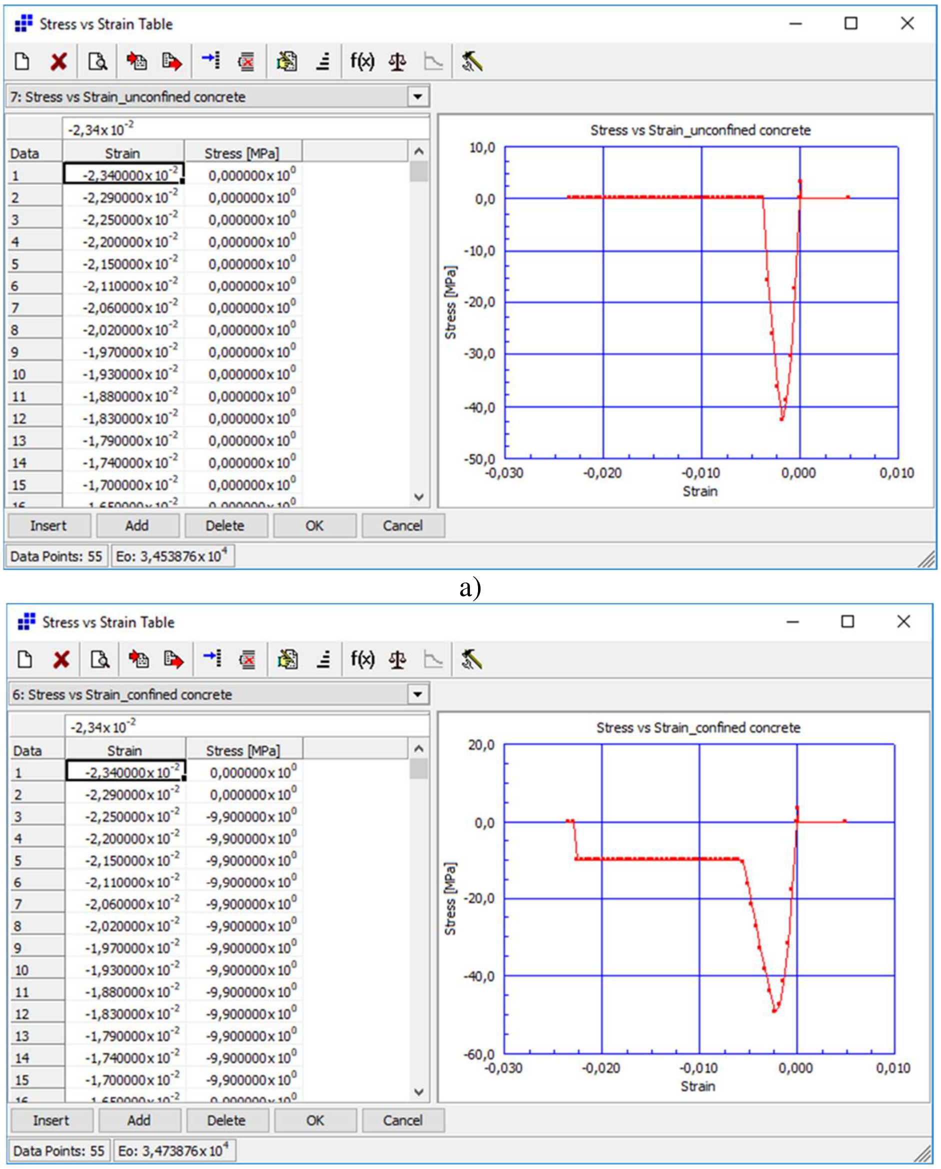

Figure 17: Stress-strain curves for: a) Unconfined concrete; b) Confined concrete

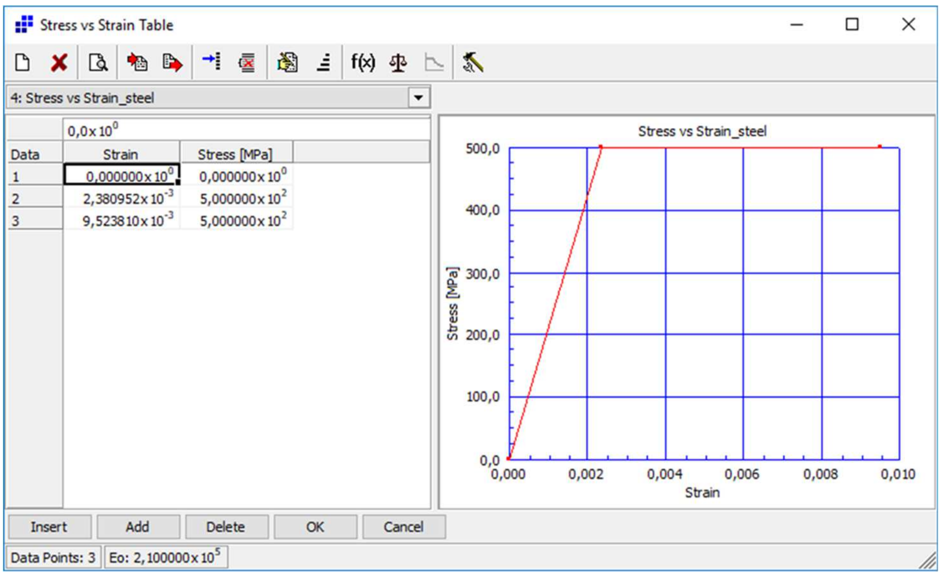

Figure 18: Stress-strain curve for steel

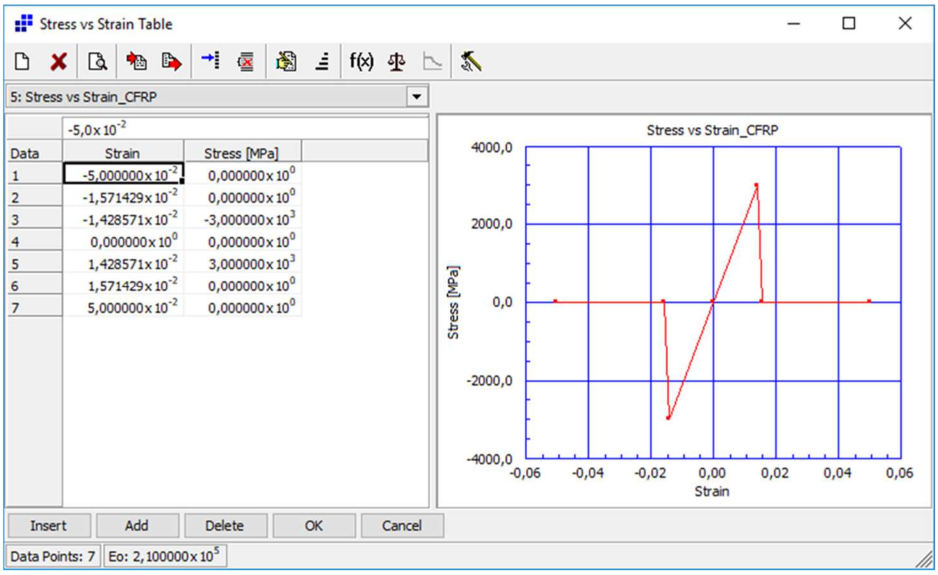

Figure 19: Stress-strain curve for CFRP laminates

Table 3 compares the theoretical predictions – based on the simplified calculation datasheet and the finite element analyses – with the experimental test results in terms of the ultimate bending moment, M_{rd}, and corresponding failure load, F_u.

Specimen	Datasheet		Finite element analysis		Experimental tests	
	F_u (kN)	M_{rd} (kNm)	F_u (kN)	M_{rd} (kNm)	F_u (kN)	M_{rd} (kNm)
1	126	139	135	148.5	155	170.5
3	380	418	397	437	398	438

Table 3: Comparison between the results of the theoretical models and experimental tests

The theoretical load-deflection curves, obtained from the finite element non-linear analyses, are compared to the experimental curves for specimens 1 and 3 in Figure 20 and Figure 21, respectively. The points corresponding to the failure of concrete, steel, and CFRP are clearly recognisable. A very good matching between the theoretical predictions and experimental results was obtained. In this respect, it should be stressed that the finite element models were not calibrated against the experimental results for the simulated tests. In fact, the theoretical models were delivered in July 2017, while the full-scale tests were conducted in August 2017.

The simplified data sheet proved to yield conservative predictions with respect to the more complex finite element models. Furthermore, both theoretical tools were conservative in predicting the experimental behaviour.

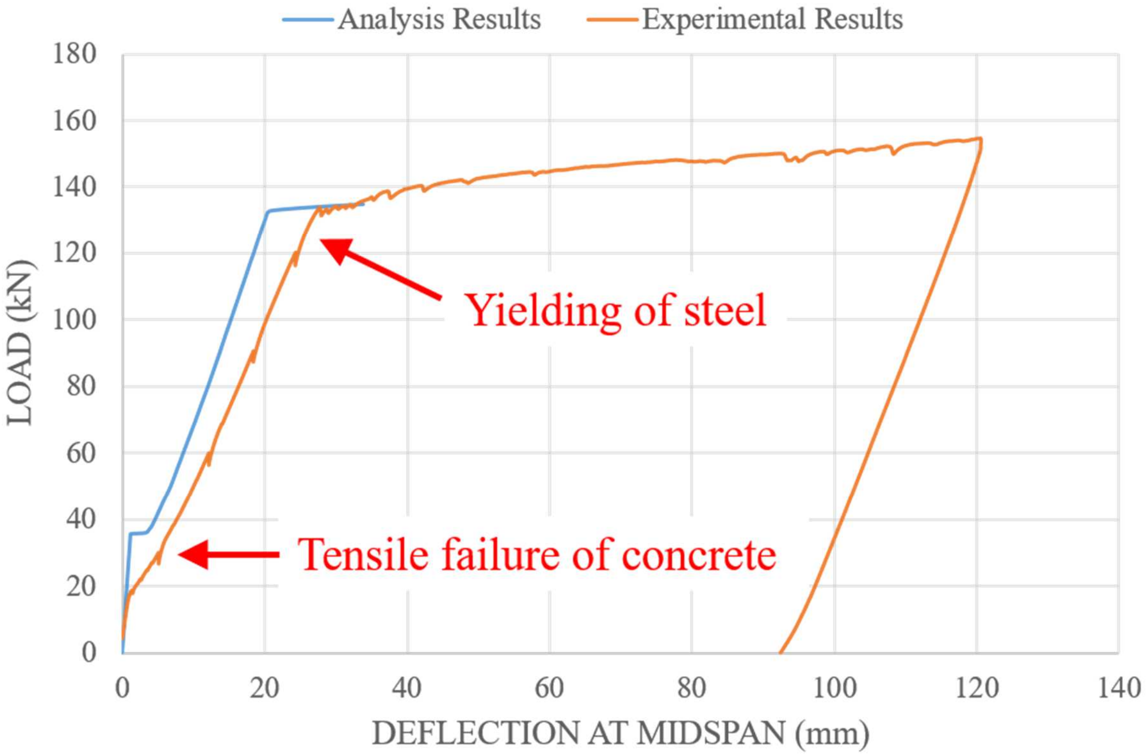

Figure 20: Comparison between the theoretical and experimental load-deflection curves – Specimen 1

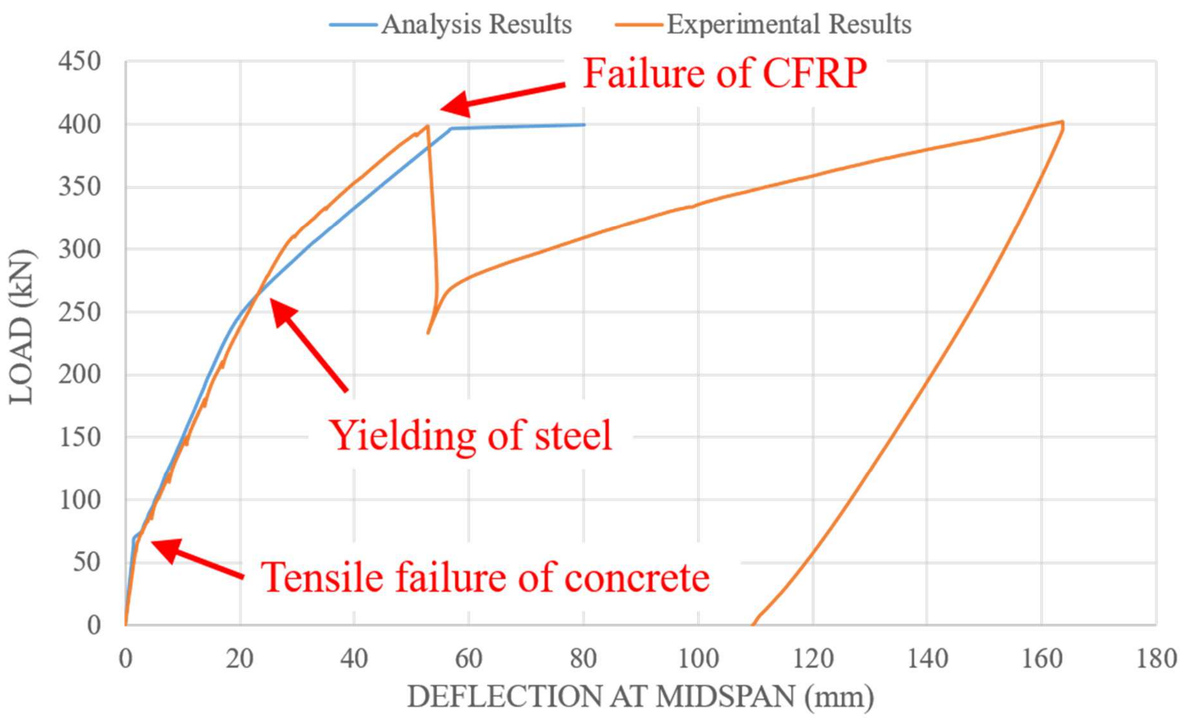

Figure 21: Comparison between the theoretical and experimental load-deflection curves – Specimen 3

Conclusions

An innovative solution for the refurbishment of road bridges has been presented. The proposed technique – developed within the European project SUREBridge – can be applied to bridges with reinforced concrete slab and longitudinal girders made of either reinforced concrete or steel. Longitudinal girders are strengthened by bonding pre-stressed CFRP laminates to their bottom surfaces. GFRP panels are connected to the deck to increase its overall bending strength and to widen the road section, if necessary.

The effectiveness of the proposed technique has been demonstrated through laboratory tests on full-scale prototype beams. The observed structural response has been predicted based on finite element non-linear analysis. Besides, the failure loads have been predicted based on a simplified ULS calculation model. For the analysed cases, a good matching between theory and experiments has been obtained with both theoretical tools yielding slightly conservative strength predictions.

It should be also noted that the theoretical calculations have been based on nominal values of the material properties. Currently (October 2017), mechanical tests on material samples are being carried out. Their results will be used to update the theoretical models in the hope of obtaining even better agreement with experimental results.

Acknowledgements

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References

[1] SUREBridge – Sustainable Refurbishment of Existing Bridges: http://surebridge.eu/

[2] FiberCore Europe: http://www.fibercore-europe.com

[3] Haghani R., Al-Emrani M., Kliger R.: "A new method for strengthening concrete structures using prestressed FRP laminates", 8th International Structural Engineering and Construction Conference (ISEC 2015), Sydney, Australia, November 23–28, 2015

[4] Strand7 Pty Limited: "Strand7 Software Theoretical Manual – Theoretical background to the Straus7 finite element analysis system", 1st Edition. Sydney, Australia, 2005

[5] EN 1992-1-1:2004: "Design of concrete structures – Part 1-1: General rules and rules for buildings"

[6] Kent D.C., Park R.: "Flexural members with confined concrete", Journal of the Structural Division, Proc. of the American Society of Civil Engineers, 97(ST7), 1971, pp. 1969-1990