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CALCULUS OPTIMIZATION OF A STRENGTHENING METHOD FOR A REINFORCED CONCRETE BEAM USING CARBON FIBRE REINFORCED POLYMER COMPOSITES

BY

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Abstract. In recent years, the need to rehabilitate / consolidate the existing built-up fund has become of particular importance for many reasons (extension of the construction exploitation period, economic considerations, etc.).

This paper presents the results of a numerical investigation of flexural and shear strengthening of reinforced concrete (RC) roof elements (T – section beams) with externally bonded Carbon Fibre Reinforced Polymer (CFRP) strips and sheets of a water tank.

The assessment has been conducted using two software design programs. Firstly, the input data values have been collected on the basis of an experimental program. The numerical evaluation of the reinforced concrete structural element has been calculated as a simply supported beam using SCIA Engineer software program, by FEM (Finite Element Method), in order to determine the maximum values of the internal efforts (bending moment, shear force) in different load combinations.

Subsequently, based on the results obtained, the design of the consolidation solutions using CFRP has been realised with the Sika® Carbodur® FRP Design program.

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This program allows the design of flexural strengthening (using the maximum value of the bending moment) to determine the dimensions of CFRP strip and the design of shear strengthening (using the maximum value of the shear force) to determine the dimensions and the number of layers of CFRP sheet.

In the case of shear strengthening, it has been calculated two types of application of CFRP on the structural elements: continuous jacketing and discrete strips. The obtained results for both variants present some advantages and disadvantages. In both situations, the results are valid and the design is made according to the norms, conclude the fact that the use of CFRP (Carbon Fibre Reinforced Polymer) represents an effective consolidation method which can be used to repair and strengthen damaged/deteriorated beams.

Keywords: Finite Element Method; numerical evaluation; carbon fibre reinforced polymer; roof element; concrete.

1. Introduction

The need for structural improvement of the existing built-up fund is of significant importance compared to recently built structures. Several causes can lead to degradation/deterioration to the various structural elements (beams, columns, etc.), such as:

– the quality of the materials used;

– design and/or execution errors;

– inappropriate exploitation of existing objectives;

– exceptional loads;

– action of the aggressive environmental agents (freeze-thaw cycles, acid rains etc.).

Due to the degradation/deterioration of structural elements, the structural consolidation procedure represents a current problem nowadays. Bringing an existing construction objective to the requirements of the current rules can be solved by adopting an appropriate consolidation system (Karzad *et al.*, 2017).

Therefore, the consolidation of the damaged structures is essential in order to maintain and extend the service life.

2. Description of the Structural Element

The analysed construction is a ground water tank made of reinforced concrete having a capacity of 5,000 m^3. It was built in the 1980s and it is still in exploitation, providing the necessary water for the Miroslava village and the Nicolina neighbourhood in Iaşi, Iaşi county.

Due to the constant exploitation and possible execution errors, severe degradations/deteriorations (reinforcement corrosion, expulsion of the concrete layer, cracks) were identified at the level of the roof elements (Fig. 1).

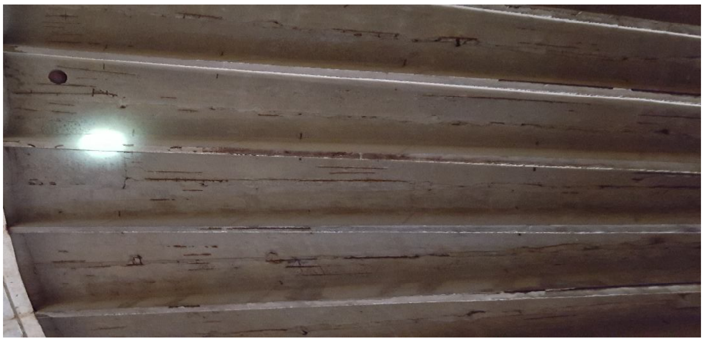


Fig. 1 − Degraded roof elements

At the top, the tank was closed with reinforced concrete T-shaped (Table 1) roof elements (Fig. 2) which are radially disposed, supporting one end on the top of the wall and the other on the central pillar cap.

Table 1
Geometry Input Data

Input data	Geometrical characteristics
1. Type of section	T – reinforced concrete;
2. Sectional dimensions ($B \times H$)	(25 – 188) × 51 [cm]
3. Web thickness	Variable: 11,...,14 [cm]
4. Flange thickness	Variable 5,...,8 [cm]

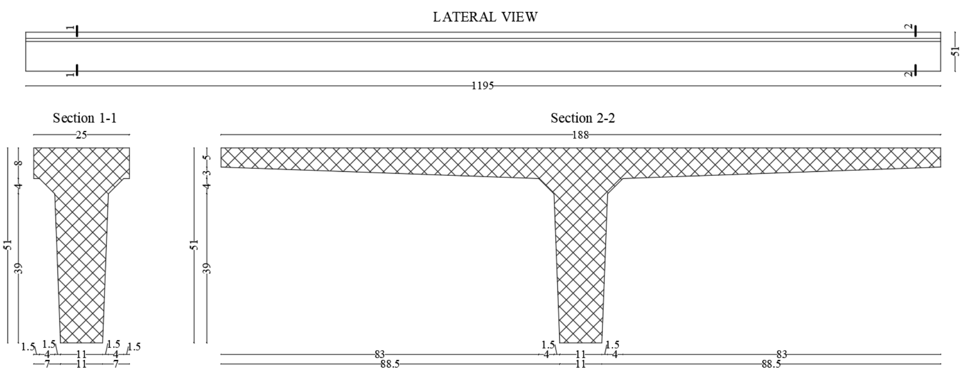


Fig. 2 − Lateral view of the structural element.

Therefore, in order to increase the durability of the structure, consolidation solutions using CFRP (Carbon Fibre Reinforced Polymer) composite materials have been computed. A numerical calculus based on an experimental program (laboratory tests) and a software analysis by FEM (Finite Element Method) was performed.

In the initial stage of the analysis, the mechanical characteristics of the materials has been collected from the experimental tests by using destructive methods, the compressive strength is $f_{ck,\text{cube}}$ = 15 N/mm^2, corresponding to the concrete class C12/15.

The materials used for the construction of the structural elements are illustrated in Table 2.

Table 2
Material Input Data

Material	Type / Class
1. Concrete	C12/15
2. Reinforcement	OB37, STNB, TBP12

3. Numerical Analysis by FEM

The structural element was modelled and analysed by using SCIA Engineer software program and the linear static analysis was performed to compute the maximum internal efforts (bending moment – M_y, shear force – V_z) according to the following model (Fig. 3).

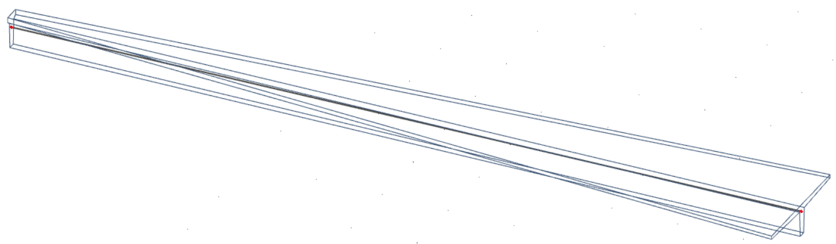
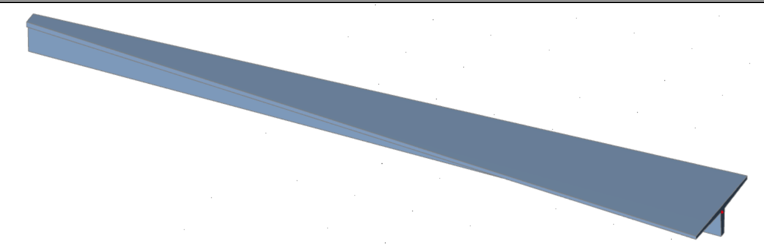
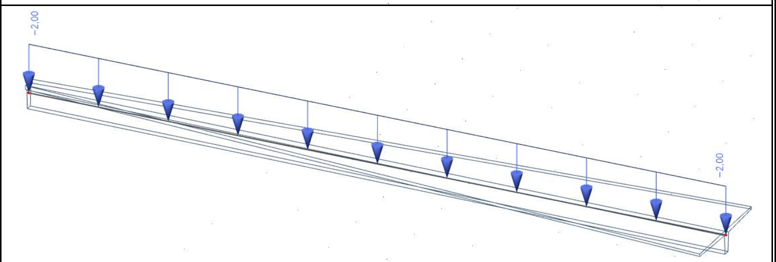


Fig. 3 − Structural element model.

The accuracy of the calculation depends on the considered static scheme introduced in the software program, which must be in line with the structural model. In this case, the structural element has been modelled as a simply supported beam.

The loads involved (Table 3) in the calculation of the structural element (roof beam) were.

Table 3
Acting Actions on the Roof Element

Loads	
1. The self-weight of the element	
2. Variable action (snow)	

The considered load combinations and the corresponding partial safety coefficients (Table 4) for the combinations of actions in ultimate limit state (ULS) and service limit state (SLS) checks are (CR0-2012).

Table 4
Load Combinations

Type of combination	Type of action	
	Permanent action (self- weight)	Variable action (snow)
1. Fundamental combination (ULS)	1.35	1.50
2. Characteristic combination (SLS)	1.00	1.00
3. Frequent combination (SLS)	1.00	0.50
4. Quasi-permanent combination (SLS)	1.00	0.40

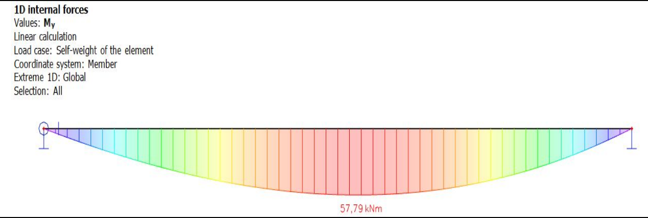
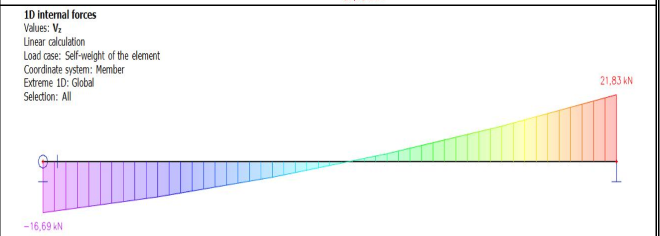
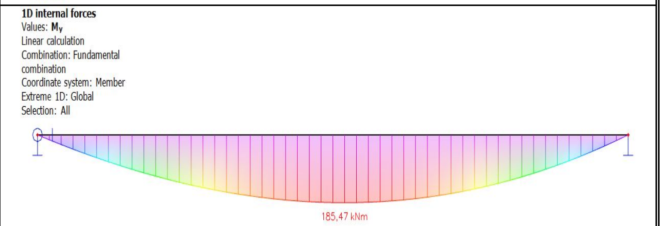
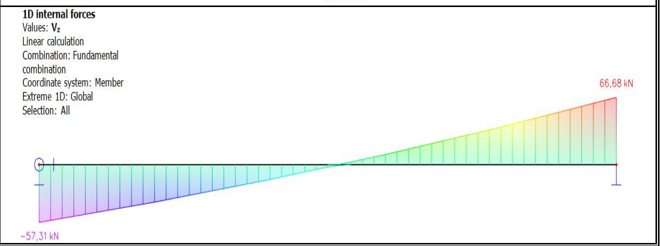
The load combinations can be calculated as in Eq. (1) (CR0-2012):

$$\sum_{j=1}^{n} P_i + \sum_{i=1}^{m} V_i , \tag{1}$$

where: P_i is the characteristic value of the permanent action; V_i – the characteristic value of the associated variable action.

The internal efforts diagrams (bending moment – M_y, shear force – V_z) of the structural element (Table 5) have been calculated by FEM using SCIA Engineer software program.

Table 5
Diagrams of the Internal Efforts

<table>
<tr><th>Type of combination</th><th colspan="2">Internal effort</th></tr>
<tr><td rowspan="2">1.
Self-weight of the element</td><td>M_y [KNm]</td><td>
</td></tr>
<tr><td>V_z [KN]</td><td>
</td></tr>
<tr><td rowspan="2">2. Fundamental combination (ULS)</td><td>M_y [KNm]</td><td>
</td></tr>
<tr><td>V_z [KN]</td><td>
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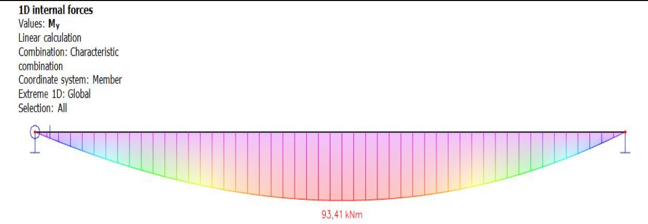
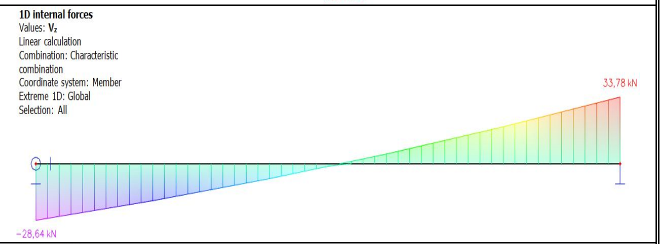
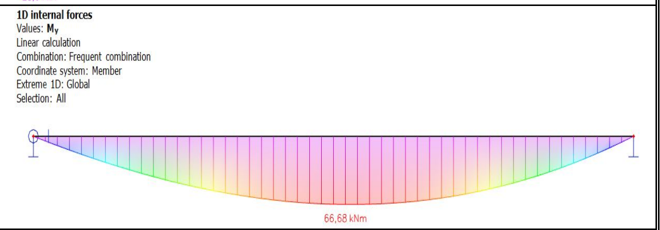
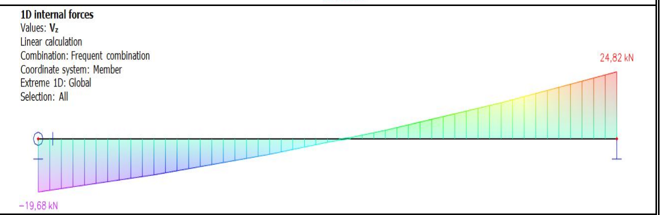
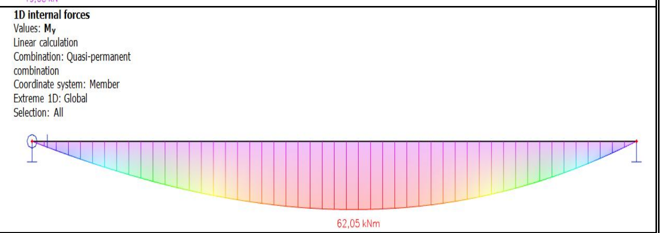
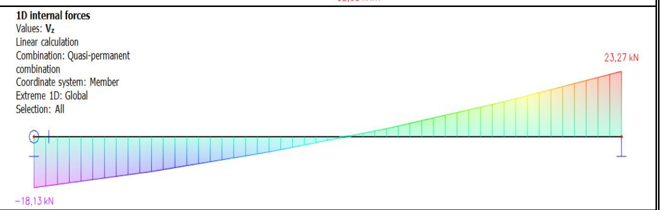
</table>

<table>
<tr><td rowspan="2">3.
Characteristic combination (SLS)</td><td>M_y
[KNm]</td><td>
</td></tr>
<tr><td>V_z
[KN]</td><td>
</td></tr>
<tr><td rowspan="2">4.
Frequent combination (SLS)</td><td>M_y
[KNm]</td><td>
</td></tr>
<tr><td>V_z
[KN]</td><td>
</td></tr>
<tr><td rowspan="2">5.
Quasi-permanent combination (SLS)</td><td>M_y
[KNm]</td><td>
</td></tr>
<tr><td>V_z
[KN]</td><td>
</td></tr>
</table>

After the analysis based on the numerical modelling was performed, the maximum values of the internal efforts (Table 6), have been quantified. Subsequently, the calculation and the checking of the consolidation solution using FRP composites has been realized using the software program Sika® CarboDur® FRP Design.

Table 6
Maximum Internal Efforts

Type of combination	Internal effort	
	$M_{y,\,max}$ [KNm]	$V_{z,\,max}$ [KN]
1. Self-weight of the element	57.79	21.83
2. Fundamental combination (ULS)	185.43	66.68
3. Characteristic combination (SLS)	93.41	33.78
4. Frequent combination (SLS)	66.68	24.82
5. Quasi-permanent combination (SLS)	62.05	23.27

4. Numerical Analysis by Sika® Carbodur® FRP Design

Sika® Carbodur® FRP Design is a software program for the design of consolidation solutions using Sika CarboDur Composite strengthening systems in order to increase the flexural, shear and confinement strength of reinforced concrete structures and elements (Sika® CarboDur®).

For the considered case study, it has been computed the flexural and the shear strengthening (in two cases: continuous jacket and discrete strips).

4.1. Flexural strengthening

The flexural strength of a reinforced concrete beam can be extensively increased by application of carbon (CFRP), plates/sheets adhesively bonded to the tensioned face of the beam (Fig. 4) (Soliman, 2018).

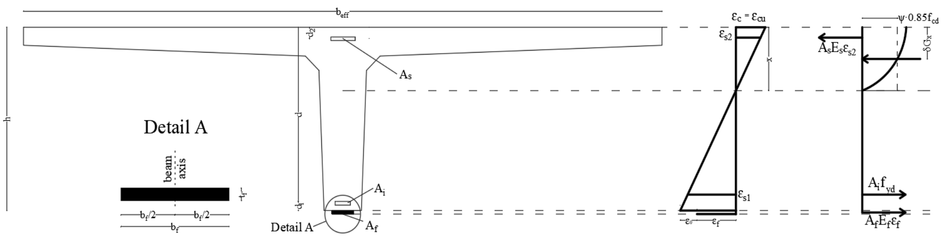


Fig. 4 – CFRP strip bonding.

Carbon Fibre Reinforced Polymers (CFRP) are being increasingly used in rehabilitation and consolidation of concrete structures and elements, since low cost comparison with other types of fibres are generally high strength-to-weight ratio, corrosion and fatigue resistance (Murali *et al.*, 2011).

Taking into consideration the maximum values of the internal efforts and the geometric characteristics of the structural element, the following numerical calculus has been performed (Table 7).

Table 7
Flexural Strengthening Results

Type of combination	Internal effort	Maximum value
1. Fundamental combination (ULS)	Resisting design moment before strengthening – $M_{rd,0}$ [KNm]	140.43
	Required FRP cross section – A_f [mm²]	38.12
	Applied FRP cross section – A_f [mm²];	60.00
	Resisting design moment after strengthening – M_{rd} [KNm];	211.20
	Degree of strengthening – M_{rd} / $M_{rd,o}$	1,504
2. Characteristic combination (SLS)	Moment capacity before strengthening – $M_{ser,r,o}$ [KNm]	126.69
	Required FRP cross section – A_f [mm²]	0.00
	Applied FRP cross section – A_f [mm²];	60.00
	Moment capacity - $M_{ser,r}$ [KNm];	133.50
	Steel stress - f_{s11} [N/mm²];	352.00
	Concrete stress - σ_c [N/mm²];	6.12
3. Quasi-permanent combination (SLS)	Moment capacity before strengthening – $M_{ser,r,o}$ [KNm]	124.52
	Required FRP cross section – A_f [mm²]	0.00
	Applied FRP cross section – A_f [mm²];	60.00
	Moment capacity – $M_{ser,r}$ [KNm];	132.35
	Steel stress – f_{s11} [N/mm²];	352.00
	Concrete stress – σ_c [N/mm²];	4.73

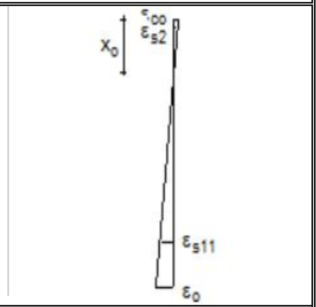
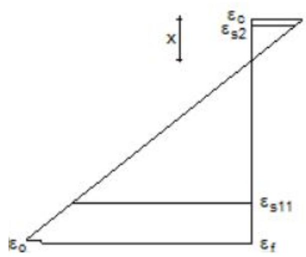
The flexural strengthening is made according by Fundamental Combination at the Ultimate Limit State, the final required fibre reinforced polymer cross section having the value A_f = 38.12 mm^2.

Dimensions of the applied FRP:

– width: b_f = 50 mm;
– thickness: t_f = 1.2 mm;
– number of strips: n = 1;
– applied FRP cross section: A_f = 60.00 mm².

Subsequently, a ductility checking has been performed on the cross-section strain profile (Table 8).

Table 8
Cross Section Strain Profile

Type of combination	Internal effort	Value	Diagram
1. Self-weight of the element – M_o	Depth of neutral axis – x [m]	0.102	
	Top fibre strain – ε_{co}	0.00025	
	Top steel strain – ε_{s2}	0.00022	
	Bottom steel strain – ε_{s11}	0.00080	
	FRP strain – ε_o	0.00101	
2. Fundamental combination (ULS) – M_{rd}	Depth of neutral axis – x [m]	0.093	
	Top fibre strain – ε_{co}	0.00314	
	Top steel strain – ε_{s2}	0.00263	
	Bottom steel strain – ε_{s11}	0.01115	
	FRP strain – ε_f	0.01300	
	Failure Mode is Steel yielding + FRP debonding		
3. Characteristic combination (SLS) – $M_{ser,r}$	Depth of neutral axis – x [m]	0.108	
	Top fibre strain – ε_{co}	0.00060	
	Top steel strain – ε_{s2}	0.00052	
	Bottom steel strain – ε_{s11}	0.00176	
	FRP strain – ε_f	0.00122	
4. Quasi-permanent combination (SLS) – $M_{ser,q\text{-}p}$	Depth of neutral axis – x [m]	0.199	
	Top fibre strain – ε_{co}	0.00155	
	Top steel strain–ε_{s2}	0.00143	
	Bottom steel strain – ε_{s11}	0.00176	
	FRP strain – ε_f	0.00141	

Ductility checking for the Ultimate Limit State:

– $\zeta = x/(h - d_{11}) = 0.220$

– maximum $\zeta = 0.45$ → ductility requirement is satisfied.

From the numerical analysis and the ductility checking, it has been resulted that for the flexural strengthening it will be used as a consolidation solution a CFRP strip having cross-sectional dimensions ($B \times t_f$): 50 × 1.2 mm.

4.2. Shear strengthening

In the situation when the shear strengthening calculation is performed, the CFRP material in this method of installation can take the form of discrete strips spaced at some interval defined by the design engineer or it can take the form of a continuous jacketing in which the entire concrete element is covered with a wrap of CFRP material. (Atif *et al*., 2007).

4.2.1. *Continuous Jacketing*

The most efficient shear application of CFRP is one that completely wraps the concrete element (Fig. 5). Complete wrapping of the element strengthens the beam in shear and eliminates any possibility of a debonding failure (Kim *et al*., 2012).

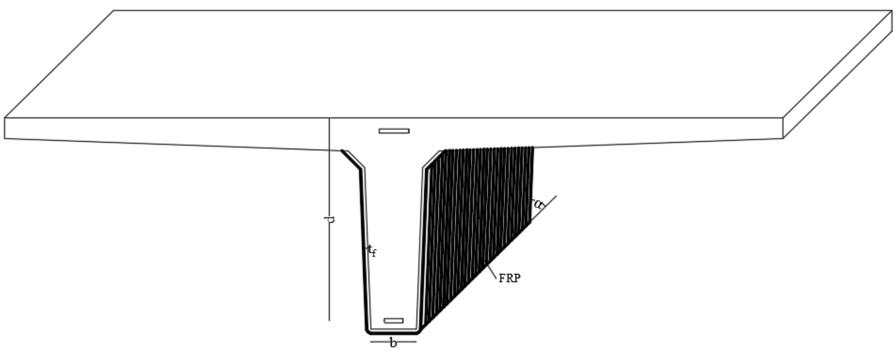


Fig. 5 − CFRP sheet - continuous jacketing

Results:

– required FRP thickness: $t_f = 0.56$ mm;

– applied FRP thickness: $t_f = 0.68$ mm;

–additional shear: $V_{fd} = 82{,}03$ [KN].

Applied FRP:

– thickness: $t_f = 0.34$ mm;

– number of layers required: $n = 2$.

As a result, from the numerical calculation, the CFRP consolidation method (continuous jacketing) will be applied on the structural element (Fig. 6).

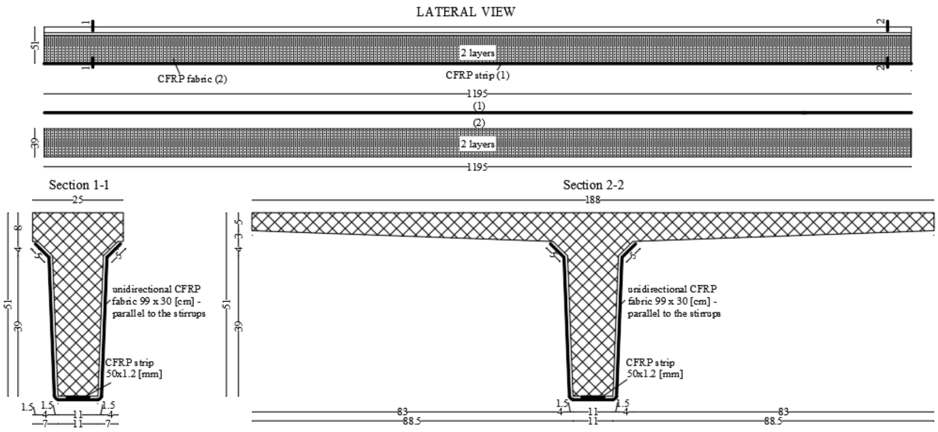


Fig. 6 − CFRP consolidation – continuous jacketing

4.2.2. *Discrete Strips*

For external CFRP reinforcement in the form of discrete strips, the centre-to-centre spacing between the strips should not exceed the sum of $b/4$ plus the width of the strip (Fig. 7). This limitation requires that a minimum number of CFRP strips cross the critical section (Mofidi *et al*., 2011).

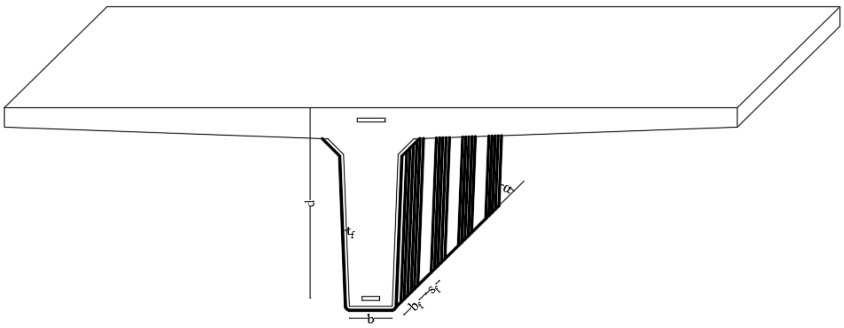


Fig. 7 − CFRP sheet – discrete strips.

Results:

– required FRP thickness: t_f = 0.56 mm;
– applied FRP thickness: t_f = 0.68 mm;
– additional shear: V_{fd} = 82.03 KN.

Applied FRP:

– thickness: t_f = 0.34 mm;

– number of layers required: n = 2.

As a result, from the numerical calculation, the CFRP consolidation method (discrete strips) will be applied on the structural element (Fig. 8).

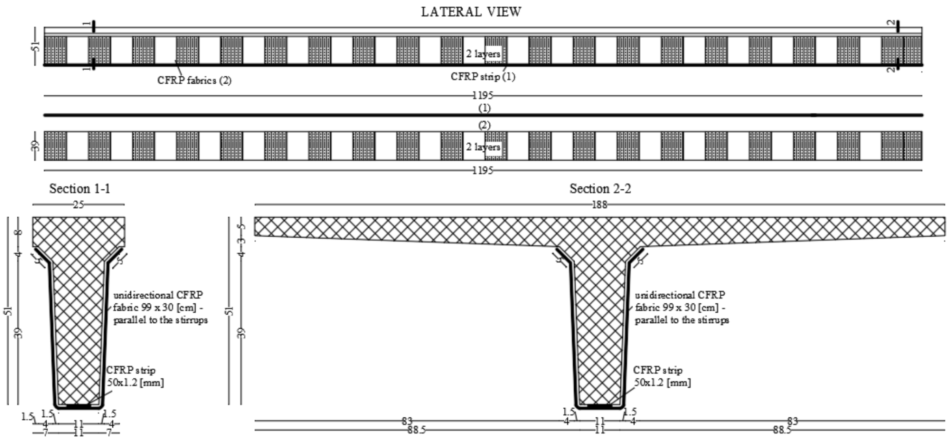


Fig. 8 − CFRP consolidation – discrete strips

5. Conclusions

A simply supported beam (T – section) has been calculated in order to predict the flexural and shear strengthening capacity of the structural element using Carbon Fibre Reinforced Polymer (CFRP). In both situations, the obtained results are valid and the design is made according to the norms.

In the case of flexural strengthening design, based on the maximum value of the bending moment, the use of CFRP strips represents an effective method which can be used to repair and strengthen degraded/deteriorated beams.

In the case of shear strengthening design, both variants present some advantages and disadvantages. Continuous jacketing application represents a better option when it comes to provide the continuity of the stresses along the structural elements and increasing redundancy.

The main disadvantage of using continuous jacketing application is that it is impossible to monitor cracks or any level of degradation/deterioration visually in such applications. In order to allow the monitoring of strengthened beams, discrete strip application technique is preferred.

Carbon Fibre Reinforced Polymer strips appear to be suitable solutions of increasing considerably the shear capacity of reinforced concrete beams. This increase depends strongly on more parameters such as: number of CFRP layers, concrete strength, orientation of fibre, shear span to depth ratio and size of the beam, amount of internal shear reinforcement.

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* * * *Cod de proiectare. Bazele proiectării structurilor*, CR 0-2012.

* * * *Sika® CarboDur® FRP Composites – Repararea şi consolidarea structu-rilor.*

OPTIMIZAREA CALCULULUI UNEI METODE DE CONSOLIDARE PENTRU O GRINDĂ DIN BETON ARMAT UTILIZÂND COMPOZITE POLIMERICE ARMATE CU FIBRE DE CARBON

(Rezumat)

În ultimii ani, necesitatea de a reabilita/consolida fondul construit existent a căpătat o importanță deosebită din mai multe motive (extinderea perioadei de exploatare a construcțiilor, considerente economice etc.).

Această lucrare prezintă rezultatele unei investigații numerice a verificării la încovoiere şi forfecare a elementelor de acoperiş din beton armat ale unui rezervor de apă (grinzi de secțiune T) cu lamele şi împâslitură din fibre de carbon.

Evaluarea a fost realizată utilizând două programe software de calcul. În primă instanță, datele de intrare au fost colectate pe baza unui program experimental.

Evaluarea numerică a elementului structural din beton armat a fost realizată utilizând programul software SCIA Engineer, prin metoda elementului finit, pentru a determina valorile maxime ale eforturilor interne (momentul încovoietor, forța tăietoare).

Ulterior, pe baza rezultatelor obținute, proiectarea soluțiilor de consolidare utilizând CFRP a fost realizată cu ajutorul programului Sika® Carbodur® FRP Design.

Acest program permite verificarea la încovoiere (utilizând valoarea maximă a momentului încovoietor) pentru a determina dimensiunile lamelei CFRP şi verificarea grinzii la forfecare (utilizând valoarea maximă a forței tăietoare) pentru a determina dimensiunile şi numărul de straturi de împâslitură.

În cazul consolidării la acțiunea forței tăietoare, s-au calculat două tipuri de aplicare a CFRP pe elementul structural: cămăşuire continuă şi benzi discrete. Rezultatele obținute pentru ambele variante prezintă unele avantaje şi dezavantaje. În ambele situații, rezultatele sunt valabile şi proiectarea se face conform normelor, concluzionând faptul că utilizarea CFRP (polimer armat cu fibră de carbon) reprezintă o metodă eficientă de consolidare care poate fi utilizată pentru a repara şi consolida grinzile degradate/deteriorate.