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NUMERICAL INVESTIGATION OF THE FLEXURAL BEHAVIOR OF STEEL PLATES REINFORCED WITH HYBRID FLAX/CARBON COMPOSITE PATCHES

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Abstract
For strengthening or rehabilitation of existing structures, patches of fiber-reinforced polymers (FRP) materials are being adhesively bonded to the existing metallic structures. So far, Carbon FRP (CFRP) are the main composite materials industrially implemented for metal structural reinforcement, due to their reliability and high mechanical performances. However, multiple researchers have highlighted the negative environmental impact of synthetic composite materials, and interest is shifting towards the use and development of bio-based composite materials. This paper presents an FE numerical investigation of the use of Hybrid Carbon/Flax FRP as an alternative solution for structural reinforcement of steel plates under flexural loading. Four different configurations of patches are studied to be bonded to steel rectangular plates, and three point bending tests are numerically modelled to simulate the flexural behaviour of the assemblies. Compared to the unreinforced steel plate baseline, reinforcements C5, F5, CFFFC, and FFFCC exhibited improvements of 149%, 120%, 137%, and 145% in bending stiffness, respectively.

1. Introduction

Advanced composite materials have been employed in the civil engineering industry for many years [1]. One of the most popular use of composites in the civil engineering field is the repair and upgrading of beams in bridges and buildings. Although not as widespread as the upgrading of reinforced concrete structures, carbon fiber reinforced polymer (CFRP) is becoming a very attractive solution for the retrofitting of metallic beams, especially for cases where there are severe access constraints, or associated high costs with installation time [2]. Various research findings have established the effectiveness of strengthening metallic structures by bonding CFRP strips and proved that the load-carrying capacity and post-yielding flexural stiffness of steel beams can be significantly improved [2,3,4]. Design guidance documents have been published regarding the use of CFRP for the rehabilitation and upgrading of metallic civil engineering structures by CIRIA [5] and ICE [6].

Nevertheless, researchers have lately highlighted the important negative environmental impact of synthetic composite materials, and interest is shifting towards the use and development of natural-based composites [7]. Flax fiber has attracted increasing attention as a reinforcement material because of its low environmental impact, weight and cost compared to traditional carbon or glass fiber. The main drawbacks of flax fibers, like many other natural fibers, are their lower mechanical properties (elastic module, strength, etc.), and poor hygrothermal behavior. Natural fiber reinforced polymers (NFRP) are therefore limited to sub-structural applications such as interior automotive or aircraft parts, sports, music instruments, among others [8].

Hybridizing flax and carbon fibers is considered an interesting and effective method to overcome the mechanical shortcomings of flax fibers. By investigating the right hybrid modes and stacking sequences, hybridization technique may combine the advantages of both flax fibers (environmental friendliness, low cost) and carbon fibers (higher mechanical properties and hygrothermal resistance).

In this paper, a 3D solid FE model was built, to investigate the flexural behavior of a steel rectangular plate, reinforced by bonding a composite patch on its tension flange. Four different patch configuration consisting of CFRP, FFRP and hybrid Carbon/Flax composites are studied. Three point bending tests are numerically simulated to assess and compare the flexural stiffness values of the modelled specimens.

2. FE Modelling

2.1. Model description

A 3D solid model is designed to investigate the flexural behaviour of a steel rectangular plate, reinforced by bonding a smaller rectangular composite patch to its tension flange. Three point bending tests are modelled to assess the flexural gain of the assemblies and compare them to those of a non-reinforced reference steel plate. Figure.1 presents the geometries of the designed specimens and their dimensions. Four different composite configurations are studied, and consist of either carbon fiber reinforced epoxy (CFRP), flax fiber reinforced epoxy (FFRP), or hybrid carbon-flax reinforced epoxy. All modelled composite patches contain five plies. According to a previous work from the authors [9], and a study by Wang et al. [10], CFRP and FFRP plies are chosen to be 0.3mm and 0.5mm thick, respectively. Table.1 presents relevant details of the used configurations.

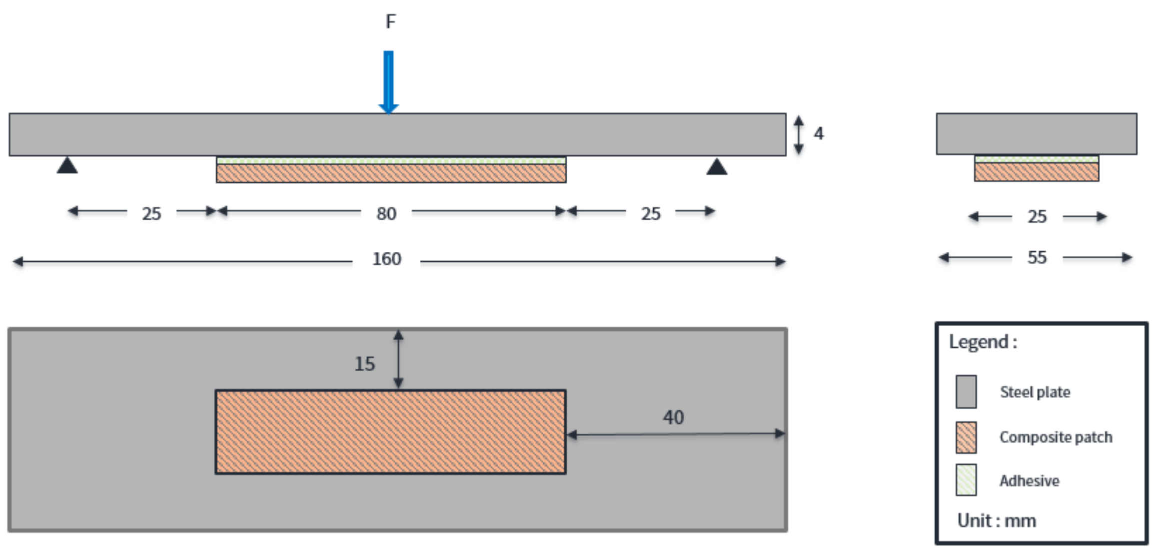
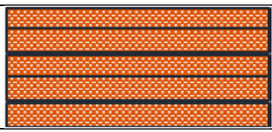
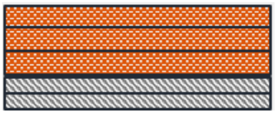


Figure 1. Schematic of a composite-strengthened steel plate.

Table 1. Composite patch configurations.

Configuration name	Representation	Nominal thickness [mm]	CFRP relative thickness	Number of CFRP plies	Number of FFRP plies
C5		1.5	1.5	5	0
F5		2.5	0	0	5
CFFFC		2.1	0.6	2	3
FFFCC		2.1	0.6	2	3

2.2. Material properties

2.2.1. Steel

A36 steel is a very commonly used material in bridge construction, and is chosen as the metallic substrate to be reinforced. Since the purpose of the study is to assess flexural gain, its behaviour is approximated with a simple bilinear elastic-plastic law, in accordance with material properties provided by the American Society of Testing and Materials (ASTM A36 Steel) [11]. Figure.2 displays the stress-strain behaviour and table.2 summarizes the used steel mechanical properties for FE modelling.

Figure 2. Stress-Strain bilinear law for A36 Steel.

Table 2. Mechanical properties of A36 Steel and adekit a-140 adhesive.

Mechanical properties	Value	
	A36 Steel	Adekit a-140
Young's Modulus [GPa]	200	2.5
Poisson Ratio	0.26	-
Yield Tensile Strength [MPa]	250	-
Ultimate Tensile Strength [MPa]	450	30

2.2.2. Composite patch

Unidirectional carbon fibers and bidirectional flax fibers with an epoxy matrix are used as reinforcement materials for the steel substrate. Table.3 summarizes their mechanical elastic properties, which were experimentally characterized in previous studies [12], [13]. We note that all laminates have 0° ply orientation relative to the longitudinal axis of the steel plate.

Table 3. Mechanical properties of composite materials.

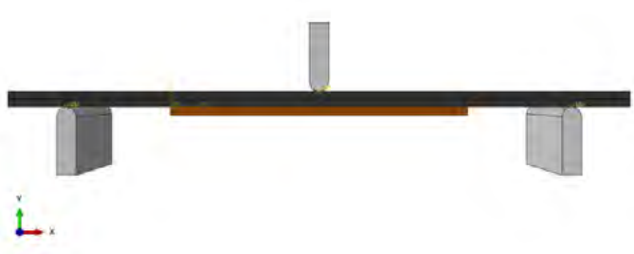
Mechanical properties	Symbol	Values	
		CFRP	FFRP
Elastic tensile Modules [GPa]	E_1	105.5	13.81
	E_2	7.2	13.81
	E_3	7.2	5.32
Shear Modules [GPa]	G_{12}	3.4	1.58
	G_{13}	3.4	1.64
	G_{23}	2.52	1.64
Poisson ratios	ν_{12}	0.34	0.144
	ν_{13}	0.34	0.51
	ν_{23}	0.378	0.51

2.2.3. Adhesive (cohesive contact)

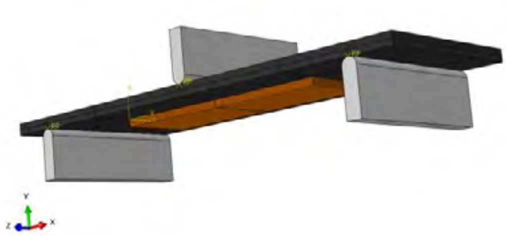
A cohesive contact interaction has been created between the top surface of the composite patch and the bottom surface of the steel substrate, to simulate the bond behaviour which would result from using the epoxy adhesive adekit a-140. Table.2 gives relevant mechanical properties of the adhesive. The cohesive zone was modelled as an elastic non-damageable interaction, because we are exclusively interested in assessing the flexural gain prior to debonding in this study. Traction-separation stiffness coefficients were all taken equal to the young's modulus of the adhesive, in accordance with the values provided by the supplier data sheet [14], $K_{nn} = K_{ss} = k_{tt} = 2500$ MPa.

2.3. Three point bending test

Three point bending test set up is designed to assess the flexural behavior of the reinforced steel plates. Figure.3 gives a visual representation of the CAE model. Fixtures were designed as rigid body parts. Contact interactions were created between the fixtures and the steel plate, and consist of a normal "hard" contact behavior and tangential friction behavior, with a friction coefficient equal to 0.15, as advised from literature for steel-steel contact [15]. 6mm displacement loads are imposed for all studied configurations.



a) Front view



b) Perspective view

c) Bottom view

Figure 3. Visual representation of the CAE model.

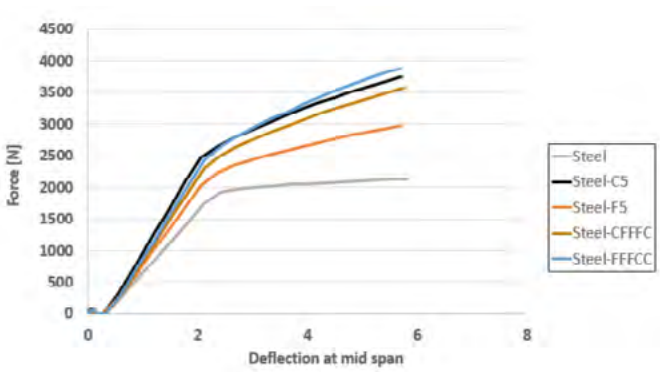
3. Numerical results and discussion

3.1. Force-deflection results

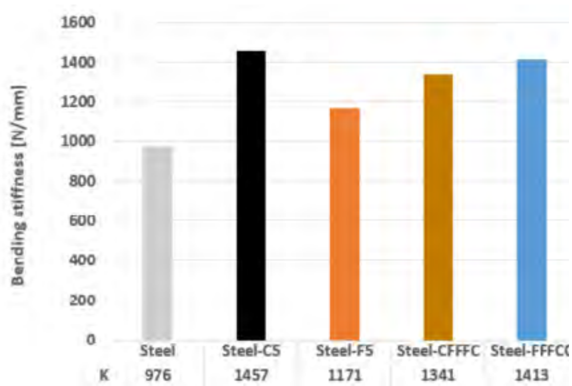
Figure.4.a) represents the force-deflection curves numerically obtained. In order to compare the flexural gain due to the bonding of the composite patches, we calculate the bending stiffness *K* within the elastic domain (between 0.5 – 2mm of deflection) with the following equation:

$$K = \frac{p}{w} \tag{1}$$

Where *p* is the applied load measured at the reference point of the moving fixture, and *w* is the deflection at mid span of the composite plate.
The bending stiffness values, depicted in Figure 4.b), highlight significant enhancements for steel plates reinforced with used configurations. Specifically, compared to the unreinforced steel plate baseline, reinforcements C5, F5, CFFFC, and FFFCC exhibit improvements of 149%, 120%, 137%, and 145% in bending stiffness, respectively. We note that the higher flax fiber ply thickness, acts like a geometrical compensation for their lower mechanical properties compared to carbon fiber plies.



a) Force-deflection curves



b) Bending stiffness for each configuration

Figure 4. Force-deflection simulation results.

3.2. Evaluation of zone of maximal stress

Figure.5 shows the longitudinal stresses S_{11}, along the thickness of the composite patches, at the end of the load history, for the four tested configurations. We notice that the patches are exclusively loaded in tension, which is due to the higher traction forces of the steel bottom flange compared to the compression of the composite patch top surface because of the curvature. From figure.5, we can also perceive that the highest stresses in the patches are contained in their bottom surfaces. This explains the high values of bending stiffness increase obtained with the CFFFC and FFFCC configurations.

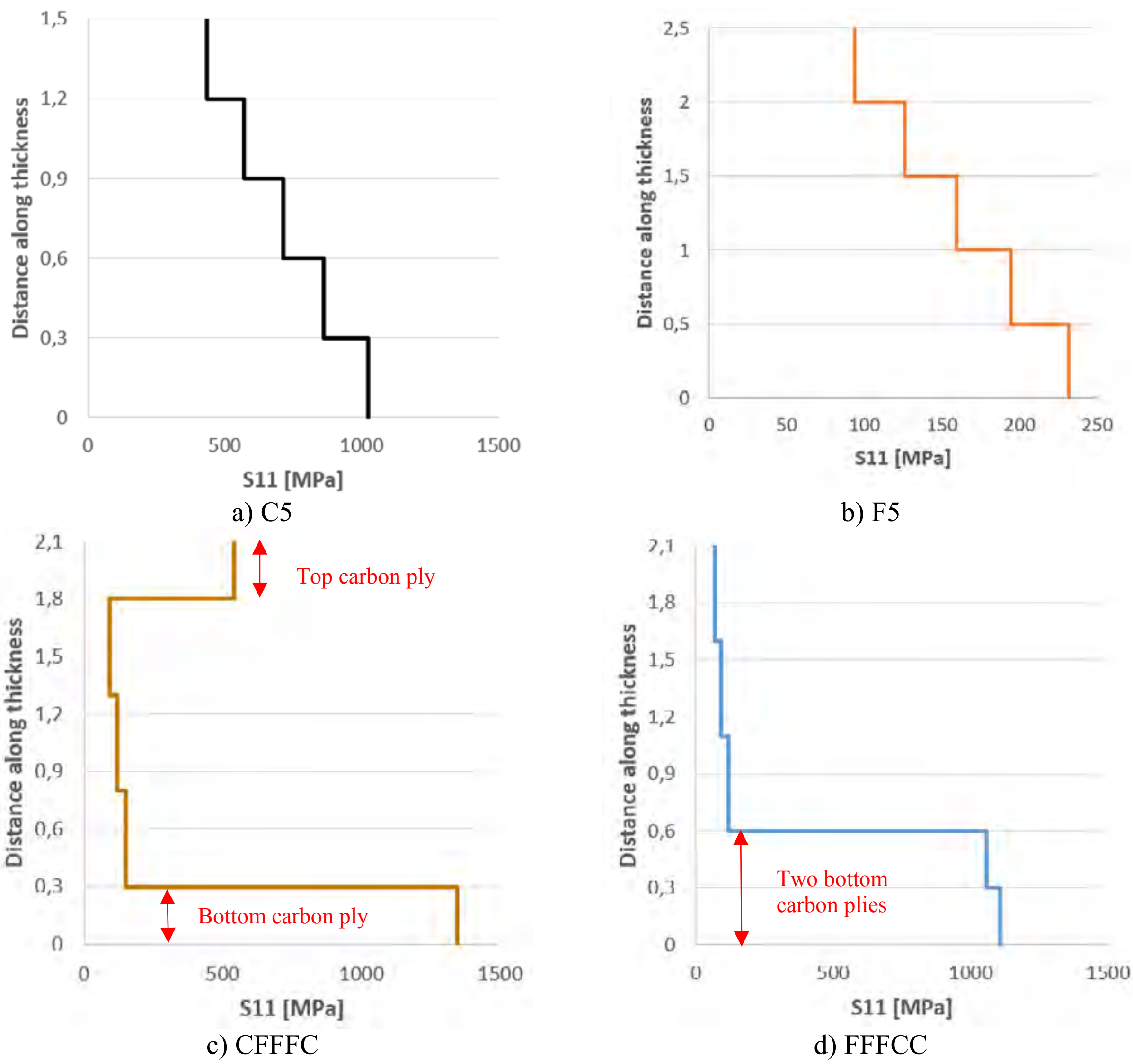


Figure 5. Distance along the thickness of the composite patches vs longitudinal stresses at mid-span

4. Conclusion

The aim of this work is to establish a finite element model to investigate the flexural stiffness gain of a steel plate reinforced by bonding a composite patch to its tension flange. Four different patch configurations consisting of CFRP and FFRP have been used, namely C5, F5, CFFFC and FFFCC. From the analysis of the obtained results, the following conclusions are drawn:

- Compared to the unreinforced steel plate baseline, reinforcements C5, F5, CFFFC, and FFFCC exhibit improvements of 149%, 120%, 137%, and 145% in bending stiffness, respectively. It is of interest to note that we achieve relatively close flexural stiffness gain with hybrid carbon/flax configuration compared to C5, while substituting 60% of carbon fibers with flax fibers.
- For various composite manufacturing processes, the choice of number of used fiber plies is the main design parameter. This study highlights the fact that natural fibers usually achieve a higher thickness per ply compared to synthetic composites, which is an interesting way of geometrically compensate their lower mechanical properties in flexural loading.
- FFFCC configuration showed the best mechanical performances after C5. Indeed, since both carbon plies are place at the bottom surface where maximal stresses evolve. Moreover, Flax fibers are the ones in contact with the steel interface, which limits risks of galvanic corrosion caused by carbon-steel contact.

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