International Journal of Engineering

Journal Homepage: www.ije.ir

Enhancement of Stiffness in GFRP Beams by Glass Reinforcement

F. Marchione*

Dipartimento di Ingegneria Civile, Edile e Architettura (DICEA), Università Politecnica delle Marche, via B. Bianche, Ancona, Italy

PAPER INFO

Paper history:
Received 13 Decemeber 2020
Received in revised form 30 December 2020
Accepted 11 January 2021

Keywords:
Bending Tests
GFRP Beams
Adhesive Joint
Stiffness Enhancement

ABSTRACT

Glass is a stiff material with brittle structural behaviour. Hence, it is usually a material mostly decorative or simply structurally supported, and it is hardly ever a load-bearing element within a structure. Although in recent years there have been several experiments in its use in civil engineering, to date little data has been collected or design methodologies disseminated. The present study proposes the innovative concept of considering glass as a structural material, cooperating within a structural system thanks to the adhesive joining technique. In detail, the case of a GFRP structural beam element subjected to bending is herein considered. The evaluation of the stiffness of the mentioned element is compared with that of the same element reinforced with glass plates of different thicknesses. The results show the possibility to increase the global stiffness of the structural element. These outcomes are validated by FEM analysis, which showed excellent agreement with the analytical ones. The effectiveness of the reinforced system, thanks to the considerable stiffness characteristics, allows both the use of glass and the respect of the requirements related to the displacements of the structural elements in their service life.

***doi**: 10.5829/ije.2021.34.03c.04*

NOMENCLATURE

URM	Unreinforced model	k	Stiffness
RM-i	Reinforced model with i–thick reinforcement	E	Young Modulus
I	Moment of inertia	b	Cross area width
t	Thickness	l	Beam Length
s	Displacement	F	Applied load

1. INTRODUCTION

Glass is a stiff material with brittle structural behaviour. In the building sector, there has been a significant increase in its use [1-3]. In fact, it is an element that allows light spaces to be created and gives a sense of lightness to the resulting element. However, despite the fact that the use of glass is very frequent (e.g. doors/windows [4], decorations, etc.) its structural applications are limited to date. In fact, in its usual applications, it is often configured as a supported object without any load-bearing function. Recent scientific and research advances are considering the development of glass or hybrid structures, characterised by the joining of glass with other traditional materials, such as timber [5-7], steel [8], GFRP [9].

However, in the study of these new structures, the main point is represented by the joints. In fact, joints are the most vulnerable points in any structure. In particular, in the case of glass structures, classical mechanical joints introduce undesirable concentrated stresses due to the brittle behaviour of glass. Stress peaks could lead to the diffusion of micro-cracks and therefore the rapid collapse of the structure or part of it for values of stresses lower than those characteristics of the material.

Therefore, the types of joints that could overcome this type of problem are the adhesive ones.

This type of joint provides several advantages, such as better and more uniform stress distribution, ease of application and little added weight to the resulting structure [10, 11].

Several papers, such as in Refs. [12, 13] show how the use of glass (a fragile material) coupled with other

*Corresponding Author Institutional Email: f.marchione@pm.univpm.it (F. Marchione)

Please cite this article as: F. Marchione, Enhancement of Stiffness in GFRP Beams by Glass Reinforcement, International Journal of Engineering, Transactions C: Aspects Vol. 34, No. 03, (2021) 615-620

ductile materials (steel, GFRP, aluminium, timber) is able to create high-performance structures, capable of withstanding significant external actions both in and out of plane.

Parate [14] studied Propellant Actuated Devices (PAD), usually installed on various combat aircraft of Air Force. This study explains the development aspects of PAD, its use, function, testing and performance evaluation methodology in a suitable fabricated Velocity Test Rig (VTR). The main objective of this paper is to device a novel method to measure actual slug velocity of the aircraft gun inside a cartridge using VTR and Doppler RADAR. Ntintakis et al. [15] studied the topology optimization by the use of 3D Printing Technology in the Product Design Process. In this study the authors initially print furniture models with different wall thicknesses using the Inject Binder technique and then we check their durability and resilience by compression tests. Then, the optimized models are redesigned in order to improve their durability. Ha [16] proposed a simple but effective trailing edge flap system. This preliminary concept uses a more practical and stable actuation system which consists of a motor-driven worm gear drive and flexible torsion bar. A preliminary level design study was performed to show the applicability of the new trailing edge flap system for wind turbine rotor blades or helicopter blade. Rastegarian et al. [17] studied the dependency of structural performance level and its corresponding inter-story drift in conventional RC moment frames. For this purpose, inter-story drift as a dependent variable and other structural characteristics have been assumed. Specimens were studied by means of pushover analysis.

Silvestru et al. [18] studied two configurations for such glass-metal façade elements, with silicone and acrylic adhesive respectively. Full-scale tests and FEA simulations are carried out for the two configurations with loads acting in three different directions, both separately and in combination. The results of the tests performed under in-plane shear load reveal a high load capacity of both configurations and show that the failure begun inside the adhesive layers.

Haldimann et al. [19] studied the performance of five adhesives for load-bearing steel-glass connections. Mechanical tests on the connections provided useful data for the selection of a suitable adhesive (silicone).

Richter et al. [20] illustrated the possibilities offered by existing hyperelastic material models for specific steel-glass components. Small-scale tests were carried out to characterise the adhesives and determine the material model for subsequent FEA.

Figure 1 illustrates the research methodology proposed.

Glass-fiber-reinforced pultruded materials (GFRP) represent innovative high-strength materials with low dead weight. However, they are particularly vulnerable

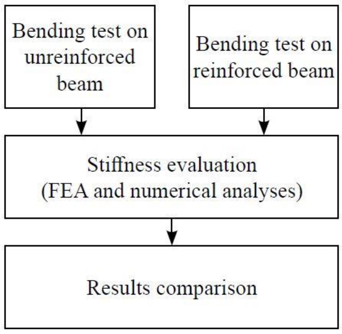

Figure 1. Research flowchart

to concentrated stresses (e.g. bolted joints). Therefore, the adhesive joint allows both to solve the problem of stress distribution and to improve the global behavior of the resulting structure, making the glass and the support beam structurally cooperating [21].

This paper illustrates the study of the problem of a GFRP beam and illustrates a simple method to improve its characteristics in terms of the overall stiffness of the structural element. This is sought through the insertion of a glass plate reinforcement at its extrados. The analytical and numerical methods for the evaluation of the stiffness of the structural configurations analysed are detailed in the following.

2. PROBLEM STATEMENT

In this section the simulations and calculations program carried out is defined.

The present paper illustrates the possibility of obtaining a significant increase in stiffness by means of an adhesive joint between a GFRP beam and a glass plate. GFRP and glass panels are bonded together by means of structural adhesive, as shown in Figure 2. The cross-section of the beam is depicted in Figure 2, and it will be analysed in the following. Numbers 1 and 2 indicate the GFRP and glass substrates, respectively. The adhesive thickness between the adherents is always considered constant and equal to 0.30 mm. The length of the beams is always considered to be 1.00 m.

Figure 3 illustrates the static scheme used in the subsequent analytical analysis. A pressure of 2.00 kPa is applied to the extrados surface of the beam.

The novelty of this concept concerns the realisation of a new type of load-bearing beam for structural uses, characterised by the coupling of a ductile material (e.g. GFRP) and a material known to be brittle (e.g. glass). The reinforcement by means of a glass plate is proposed only on the extrados of the beam both for architectural needs (e.g. transparent and light finish) and for needs related to the safety of the users.

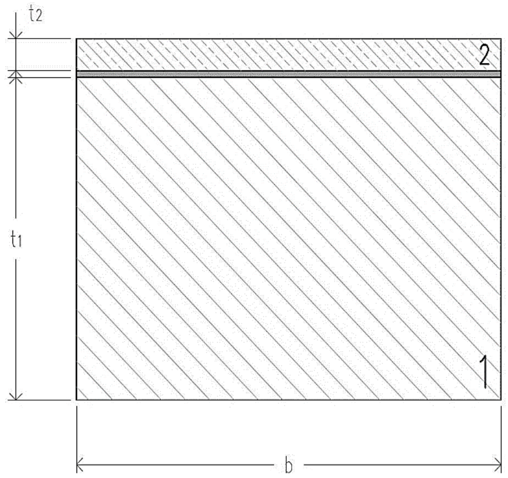

Figure 2. Beam cross section

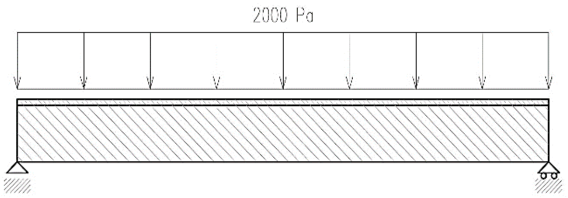

Figure 3. Static model of the beam

Table 1 shows the mechanical characteristics of the materials used in the models shown below.

Table 2 illustrates the acronyms and geometric characteristics of the beams considered in the following analyses

The results obtained from analytical calculations and FEM simulations are shown below.

TABLE 1. Materials' characteristics

	E [MPa]
Adhesive	3000
GFRP	26000
Glass	75000

TABLE 2. Beams geometric characteristics

Parameters				
Specimen	**b (mm)**	**t_1 (mm)**	**t_2 (mm)**	**l (mm)**
URM	70	50	-	1000
RM -10	70	50	10	1000
RM -15	70	50	15	1000
RM -20	70	50	20	1000

3. ANALYTICAL MODEL

Considering the static model of the beam (Figure 2) simply supported at its ends, the following equation could be written in relation to the value of the beam displacement:

$$s = \frac{F\, l^3}{48\, E_b\, I_b} \tag{1}$$

where *l* is the length of the beam, E_b is the modulus of elasticity and F is the applied load. I represents the moment of inertia of the beam, given by the well-known equation:

$$I = \frac{b\, h^3}{12} \tag{2}$$

where b e t_b are width and length of the beam cross-section, rispectively.

Stiffness *k*, defined as the load required to produce a unit displacement, is given by the following:

$$k = \frac{F}{s} = \frac{48\, E_b\, I_b}{l^3} \tag{3}$$

To verify the effectiveness of the reinforcement in terms of stiffness, it is necessary to distinguish between perfectly adhesive behaviour between glass and substrate and no structural collaboration between the two elements. In the case of structural collaboration, the stiffness could be evaluated as follows:

$$k_{coop} = \frac{48}{l^3} \sum_{i=1}^{2} E_i I_i^* \tag{4}$$

in which the moments of inertia are expressed as follows:

$$I_1^* = I_1 + A_1 \cdot x^2 \tag{5}$$

$$I_2^* = I_2 + A_2 \cdot \left[(t_2 - x) + \frac{t_2}{2} \right]^2 \tag{6}$$

The position of the neutral axis in relation to the centre of gravity of the section is then determined:

$$x = \frac{E_2 \cdot b \cdot t_2 \cdot \frac{t_1}{2} + E_2 \cdot b \cdot t_2^2 \cdot \frac{1}{2}}{2\, E_1 \cdot t_1 \cdot t_2 + 2\, E_1 \cdot b \cdot t_2 + E_1 \cdot b \cdot t_2} \tag{7}$$

In the case of non-collaborating elements, the stiffness could be expressed as follows:

$$k_{no-coop} = \frac{48}{l^3} \sum_{i=1}^{2} E_i I_i \tag{8}$$

Where the moments of inertia are expressed as shown in Equation (2).

4. FEA ANALYSIS

This section illustrates finite element modeling for the above mentioned problem.

Finite element analyses are performed both in the case of unreinforced and reinforced beams, according to the geometric configurations illustrated in section 2.

The "Static Structural" module, present in ANSYS©19 is used, and the results are herein reported. The analysis is linear elastic, and the analysis is of 3D-type. The geometries illustrated are meshed with PLANE 182 elements, a 4-node structural solid and a maximum element size of 0.10 mm. Once the loads are applied, it is possible to correlate the maximum displacement with the force reactions at the ends of the beam, both for unreinforced and in reinforced beams.

4. RESULTS AND DISCUSSION

The present paragraph reports on the results obtained according to both the analytical and numerical analysis just presented.

Different geometrical characteristics have been considered in the reinforcement of the GFRP beam in the condition of cooperating reinforcement.

The beam theory is used to analyze the ductility and to evaluate the position of the neutral axis for a composite beam simply supported at its ends. The simulation validates the theoretical results by means of a linear elastic analysis of the model considered. The FEA simulation is conducted by means of the static analysis of the ANSYS©19 software. Table 3 illustrates and compares the results obtained from the different analyses.

The results obtained show a very accurate approximation of the analytical analysis for the evaluation of the stiffness increase brought by the glass reinforcement. In fact, a small evaluation error is observed for the reinforced configurations (within 15%).

Figure 4 shows the force-displacement graphs obtained from the analyses.

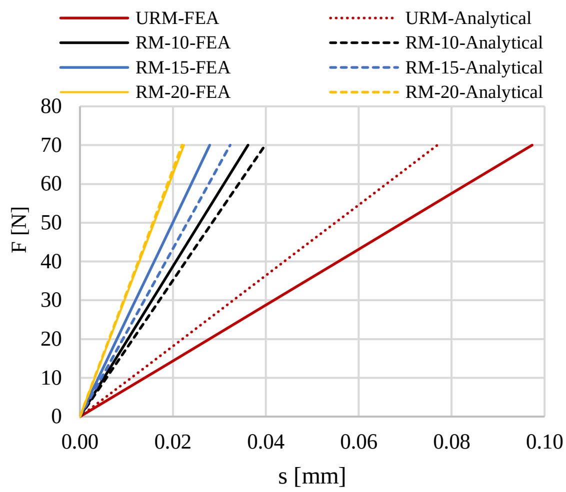

Figure 4. Load-displacement graph

TABLE 3. Analytical and FEA results

Specimen	b (mm)	t_1 (mm)	t_2 (mm)	l (mm)	*k* (N/mm)		
					ANSYS	Equation (4)	Δ (%)
URM	70	50	-	1000	719.22	910.00	-26.53
RM -10	70	50	10	1000	1934.98	1755.95	+ 9.25
RM -15	70	50	15	1000	2505.64	2165.32	+ 13.58
RM -20	70	50	20	1000	7409.29	3184.06	- 1.88

4. CONCLUSIONS

Recent legislations and technological developments lead to a continuous escalation of the technical requirements of structural elements in terms of both global and local ultimate strength. On the other hand, modern architectural language makes extensive use of glass as both a structural and purely decorative material. Indeed, glass allows the creation of luminous structures and provides an idea of lightness to the user. However, the structural applications of glass are currently very limited. The study here presented proposes a new hybrid beam in GFRP and glass for structural purpose. The result is a light and design structural element, which is therefore not relegated to a load-bearing function only, but also assumes an architectural value.

In detail, a GFRP beam in unreinforced configuration is considered and its stiffness is evaluated both numerically and analytically. Then, different combinations of glass reinforcements (i.e. plates of different thicknesses) were considered and analysed.

The main outcomes are:

- The hybrid system enables very high stiffness values to be obtained when compared with the same unreinforced structural element;
- The increase in stiffness that could be achieved makes it possible to meet very high requirements in terms of permissible displacements with the same structural elements, without introducing significant geometric changes in the section;
- FEA and analytical results are in good agreement and therefore make it possible to adequately assess

the increase in stiffness that could be achieved;

- The methodology illustrated allows for a quick and easy assessment of the stiffness contribution of the reinforcement and is therefore an effective design tool.

In conclusion, the present study provides an example of the calculation and application of glass in the field of civil engineering. The aim is to overcome the concept of glass as a material with merely decorative functions and to extend its function to the field of structures. The results reported demonstrate the effectiveness of its application in this purpose.

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Persian Abstract

چکیده

شیشه ماده ای سفت و سخت و دارای رفتار ساختاری شکننده است. از این رو ، این ماده معمولاً یک ماده عمدتاً تزئینی است و یا به سادگی از نظر ساختاری پشتیبانی می شود و به سختی یک عنصر باربر درون سازه است. اگرچه در سالهای اخیر چندین آزمایش در استفاده از آن در مهندسی عمران انجام شده است ، اما تاکنون اطلاعات کمی جمع آوری شده یا روشهای طراحی منتشر شده است. مطالعه حاضر مفهوم ابتکاری در نظر گرفتن شیشه به عنوان یک ماده ساختاری ، همکاری در یک سیستم ساختاری را به لطف روش اتصال چسب ارائه می دهد. به طور جزئی ، در اینجا یک مورد از عناصر پرتوی ساختاری GFRP تحت خمش مورد بررسی قرار می گیرد. ارزیابی سختی عنصر ذکر شده با همان عنصر تقویت شده با صفحات شیشه ای با ضخامت های مختلف مقایسه می شود. نتایج نشان می دهد امکان افزایش سختی جهانی عنصر سازه. این نتایج با تجزیه و تحلیل FEM تأیید می شود ، که توافق عالی با نتایج تحلیلی را نشان داد. اثربخشی سیستم تقویت شده ، به لطف ویژگی های قابل توجهی از سختی ، هم استفاده از شیشه و هم رعایت الزامات مربوط به جابجایی عناصر سازه ای را در طول عمر آنها فراهم می کند.